AD-A250 184

IENTATION PAGE

Form Approved
OMB No. 0704-0188

EPORT DATE: 1991

3. REPORT TYPE AND DATES COVERED: THESIS/XXXXXXXXXXXX

4. TITLE AND SUBTITLE
A Case Study of a Prolonged Sleet Event 16-17 February, 1987 and Climatology of Sleet Events for North Carolina, 1949-1989

5. FUNDING NUMBERS

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
AFIT Student Attending: North Carolina State University

8. PERFORMING ORGANIZATION REPORT NUMBER
AFIT/CI/CIA- 91-112

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFIT/CI
Wright-Patterson AFB OH 45433-6583

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for Public Release IAW 190-1
Distributed Unlimited
ERNEST A. HAYGOOD, Captain, USAF
Executive Officer

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

14. SUBJECT TERMS

15. NUMBER OF PAGES
73

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT

18. SECURITY CLASSIFICATION OF THIS PAGE

19. SECURITY CLASSIFICATION OF ABSTRACT

20. LIMITATION OF ABSTRACT

Abstract

DAVID R. MUSICK. A Case Study of a Prolonged Sleet Event: 16-17 Feb, 1987 and A Climatology of Sleet Events for North Carolina, 1949-1989. (Under the direction of Steven Businger, Gerald F. Watson and Thomas S. Hopkins).

Winter storms in the southeastern region of the United States have the potential to produce widespread regions of mixed and frozen precipitation, with serious economic and social ramifications. Due to the relative infrequency of these storms, most southeastern states are ill prepared to deal with their effects. Thus, increasing the need for accurate and timely forecasts of the type and duration of precipitation in this region.

An investigation was undertaken of an unusually prolonged sleet event that affected North Carolina on 16-17 February 1987, to identify the synoptic and mesoscale features that governed the formation and duration of the frozen and mixed precipitation. Sleet was observed from Kansas eastward across the Appalachian Mountains to the western third of the coastal plain, with accumulations of more than 20 cm occurring in the eastern portions of the Piedmont region. These accumulations resulted in collapsed roofs and the closing of some businesses and schools for more than a week. Easterly flow on the south side of a New England high pressure center resulted in unusually strong cold-air damming that forced a shallow layer of cold air at the surface south along the east slopes of the Appalachians, across Georgia and into the Gulf of Mexico. Convective activity over the Gulf of Mexico infused significant moisture into a warm southwesterly airstream in the mid-troposphere that overran the cold air.

A climatological study of sleet events over North Carolina was undertaken. It was found that sleet has a six month season for North Carolina, November to April, with January producing the greatest number of sleet events. The Piedmont region of North Carolina has the highest number of sleet occurrences followed by the mountain region. Cold air damming was found present in 38% of the sleet events over North Carolina. Spectral analysis reveals an apparent ten year cycle in sleet maxima and minima.

ACKNOWLEDGEMENTS

I would like to thank my advisory committee for their patience and guidance throughout my stay at North Carolina State University. Thanks again to Steve Chiswell and Scott Ross for their expert help in solving my computer problems. My thanks to all my friends and classmates at NCSU especially James Hammett and Lauraleen O'Connor. But most importantly, I would like to thank my wife, Joanna, for standing by me through all the long days and late nights; she means everything to me.

A CASE STUDY OF A PROLONGED SLEET EVENT
16-17 FEBRUARY, 1987
AND
CLIMATOLOGY OF SLEET EVENTS
FOR NORTH CAROLINA 1949-1989

by

DAVID R. MUSICK

A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the Degree of
Master of Science

DEPARTMENT OF MARINE, EARTH, AND ATMOSPHERIC SCIENCE

Raleigh

1991

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1. CASE STUDY OF SLEET EVENT: 16-17 February, 1987

1.1 Introduction

A winter storm moved over the Southeast U.S. on 16-17 February, 1987 and sleet was measured from Kansas to the western third of the coastal plain region with the greatest accumulation occurring in the eastern portions of the Piedmont region. Some areas of northeast Raleigh received more than 20 cm of sleet resulting in collapsed roofs and the closing of some businesses and schools for a week. Thunder and lightning were also observed in many areas of the eastern Piedmont including Rocky Mount and Fayetteville. Since sleet is normally a transitional type of precipitation, it is very unusual that it not ι ly accumulated to such depth, but also that it fell over such a wide geographical area of the state. Formation of sleet requires a layer of air of above freezing temperature aloft while the air below must be below freezing. Data recorded by the Greensboro upper-air sounding during the sleet storm showed that the temperature at 825 mb was 4 ^{O}C while at 930 mb the temperature was -15 ^{O}C. This sounding will be discussed later, but can be seen in Fig. 17.A.

The total precipitation accumulation for the sleet event of 16-17 February 1987, for the stations listed in Table 1(see climatology section) is shown in Fig. 1. The precipitation was in frozen form which included snow and sleet; due to the way the stations record the amounts of precipitation, the difference in snow accumulation and sleet accumulation cannot be distinguished. Raleigh-Durham (RDU) reported the greatest amount of frozen precipitation recorded for the sleet event with 12.7 cm; Asheville followed with 6.1 cm. Fayetteville recorded 5.6 cm and Hickory and Rocky Mount

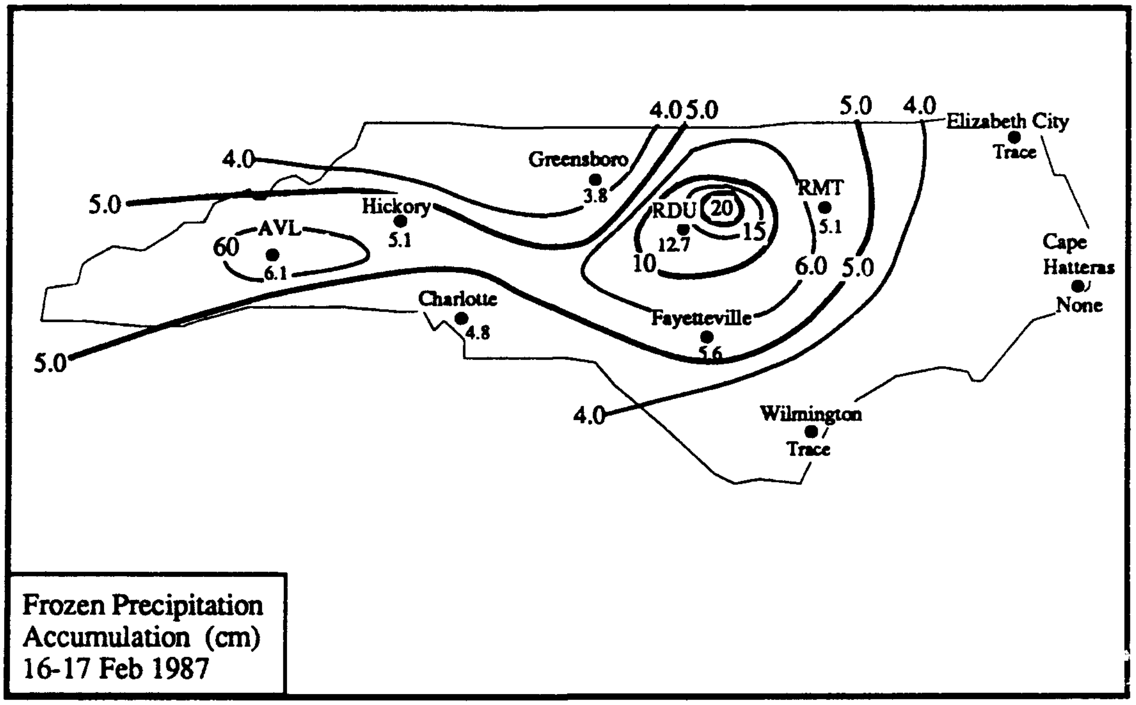

Fig. 1: The frozen precipitation accumulation for the sleet event of 16-17 February, 1987. Measured in cm.

each recorded 5.1 cm; Charlotte recorded 4.8 cm and Greensboro recorded 3.8 cm. The amount of frozen precipitation decreased in the coastal region with Wilmington and Elizabeth City recording only a trace, and Cape Hatteras having no precipitation recorded for the entire event.

The detailed observations at Raleigh-Durham are shown in Table 2. The event started at 0808 EST of 16 February, 1987 and ended at 0652 EST of 17 February, 1987. The precipitation types observed during the event include sleet, snow, and freezing rain. With the exception of two brief periods at the beginning of the event, sleet was reported in every hourly observation (Fig. 2). In fact, sleet was reported at RDU for nineteen and one-half straight hours.

The weather reports also show that sea level pressure fell steadily from 1020.2 mb to 1009.6 mb over the first 12 hours, then remained more or less constant. Temperature dipped to -5 ^{o}C, before rising steadily to -1 ^{o}C near the end of the event. Dewpoint temperature started at -8 ^{o}C then rose steadily to -4 ^{o}C. Saturation at the surface did not occur; relative humidities increased from about 70 % early in the period to about 85 % near the end. The winds were primarily out of the northeast occasionally gusting to 10 ms^{-1}.

Winter storms in the southeastern region of the United States have the potential to produce widespread sleet with serious economic and social ramifications. Due to the infrequency of these sleet storms, most southeastern states are ill prepared for their effects. One case in point was the winter storm of January 7, 1988 that moved through the southeast. A band of sleet from Columbus, Georgia to Augusta, Georgia produced two to eight centimeters of sleet on the ground causing major disruptions of travel and more than 36,000 power outages across the state. In addition, most schools and businesses were closed from two to four days (Noffsinger and Laing, 1988). Another sleet case occurred on December 8-9, 1989. A winter storm system moved through North Carolina and caused sleet and freezing rain to form across the state from Asheville,

TIME	WEATHER	PRESSURE	TEMP	DEW PT.	DIRECTION	SPEED
16 FEBRUARY, 1987						
0808	ZR-IP-				060	4G08
0825	ZR-				070	3
0831	ZR				060	5
0836	ZR-IP				030	6
0850	ZR-IP	1020.2	-4	-8	030	6
0938	ZR-IP-				020	6
0950	ZR-IP-	1019.1	-4	-7	050	6
1002	ZR-F				040	6
1009	ZR-IP-F				040	5G10
1050	ZR-F	1018.9	-4	-7	040	6
1121	ZR-IP-F				050	5
1150	ZR-IP-F	1017.8	-5	-7	060	4G08
1156	ZR-IP-F				040	6
1207	ZR-IP-F				040	5
1250	IP F	1015.8	-4	-6	080	8
1315	IP F				050	7G11
1326	IP-F				050	6
1351	IP-F	1012.7	-3	-5	050	7G10
1452	IP-F	1011.3	-3	-5	030	6G10
1550	IP-F	1010.8	-3	-5	040	7
1650	IP-F	1010.2	-4	-5	030	6
1750	IP-F	1011.3	-4	-6	010	7
1850	IP-F	1010.6	-4	-6	030	7G10
1915	IP-F				030	4
1950	IP-F	1009.6	-3	-4	030	5
2040	IP F				330	4
2050	IP F	1011.6	-3	-4	300	3
2150	IP-F	1011.1	-3	-4	010	5
2205	IP-F				340	5
2230	IP-F				320	4
2250	IP-F	1011.4	-3	-4	320	5
2350	IP-F	1010.5	-3	-4	340	6
17 FEBRUARY, 1987						
0016	IP-F				010	6
0053	IP-F	1009.8	-2	-4	360	8
0109	IP F				010	6
0123	IP-F				350	6
0145	IP-F				360	6G09
0151	IP-F	1009.1	-2	-4	340	6G10
0246	ZR-IP-F				020	6G09
0252	ZR-IP-F	1009.4	-2	-4	360	6G09
0334	S-IP-F				350	5
0353	S-IP-	1008.9	-2	-3	010	4
0450	ZR-IP-	1009.5	-1	-3	010	6G10
0550	ZR-IP-F	1010.3	-1	-3	010	5
0652	ZR-IP-F	1011.3	-1	-3	010	5

Table 2: Detailed station observations for Raleigh-Durham (RDU). Time is EST. Pressure is sea level pressure (mb). Temperature and dew point temperature is ^{o} C. Winds are in direction (0-360) and speed (m sec $^{-1}$).

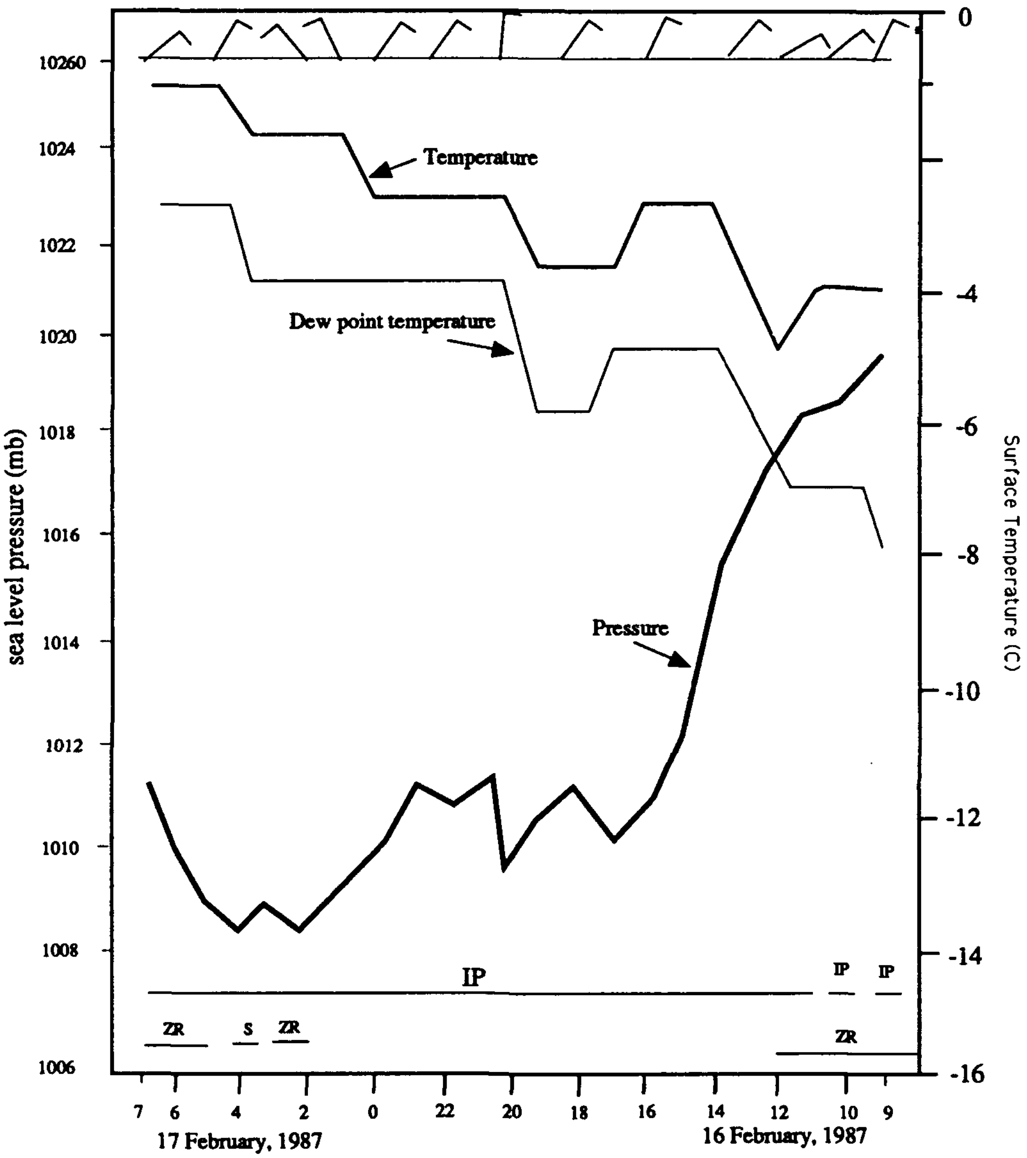

Fig. 2: Detailed station observations for Raleigh-Durham (RDU). Pressure is sea level pressure (mb). Temperature and dew point temperature are degrees C. Winds direction is 0-360 with speed in meters per second.

which received 3.3 cm, to Raleigh-Durham, which received 6.1 cm. The frozen precipitation ranged from two to ten centimeters and the resulting damage included the collapse of two 2000 foot communication antennae. In both of these cases, the amount and duration of sleet was not forecasted and the residents in those areas did not have time to prepare. These examples illustrate the need for accurate and timely forecasts of the type and duration of precipitation produced by winter storm systems.

The formation and duration of winter storms in this region has not been studied to the point necessary to accurately predict the precipitation type and amount. Cyclogenesis in the Atlantic coastal region was first documented by Miller (1946); he developed a typing of storm systems based upon origin and movement. This work has been expanded upon synoptically and studied in detail numerically (Kocin and Uccellini, 1985; Mailhot and Chouinard, 1989). Miller studied low pressure centers that formed in the Gulf of Mexico. Type "A" lows move northeast from the vicinity of the Gulf of Mexico crossing through the southeastern states east of the Appalachian mountains or along the Atlantic coast. Type "B" lows, as they approach the Appalachian mountains from the west or southwest, typically weaken and a secondary low develops further to the south and east near the Atlantic coast. Broad transition zones of a mixture of precipitation are associated with the type "B" lows or with weak poorly organized type "A" lows. Due to their relatively stable and well organized thermal structure, fully developed type "A" lows have a relatively narrow band of mixed precipitation in their transition zone.

Businger et al (1990) studied cyclone tracks that originated in the Gulf of Mexico. The authors found that 58 % of the storms moved northward along the coast on the east side of the Appalachian mountain; 27 % moved on the west side of the mountains, and 15 % moved eastward over Florida without going up the coast. They also found that the storm tracks west of the Appalachians tend to produce heavier precipitation totals across wider areas of the eastern half of the United States than those that track south and east of the mountains to the Atlantic coast. These climatological

results are useful in anticipating the precipitation pattern typical of major east coast cyclone types.

Synoptic pressure patterns can be useful in predicting precipitation amounts and duration. Bosart (1981) studied coastal fronts in the New England area; he hypothesized that cold-air pressure ridges east of the Appalachian mountains favor coastal cyclogenesis. The phenomena of cold air becoming entrenched along the eastern slopes of the mountains is referred to as cold-air damming (Richwien, 1980). The cold air is in the form of a dome, identified by a "U"-shaped pressure ridge in the sea level isobar pattern. The temperature difference can exceed 20 ^{o}C between the cold air over land and the relatively warm on-shore flow from the ocean, a distance of approximately 150 km. As a result, the cold dome can be a critical factor in determining whether precipitation falling through the cold dome will reach the ground as liquid (rain), solid (snow), or transition (sleet or freezing rain) (Penn, 1957; Chaine, 1973; Forbes *et al*, 1987).

The months of October to April account for 67 % of all damming events and 68 % of all damming days (Bell and Bosart, 1988). The winter months, especially March and December, are five times more likely, on the average, to experience a strong event than July. The number of damming events is greatest in March, with a secondary maximum in December. Furthermore, March and December average 20 % more strong events than February, and 30 % more strong events than January. Damming events are likely to be stronger than the average in December since that month represents a period in which the land is coldest relative to the ocean. A split flow regime at upper levels coupled with a maximum in southeast Atlantic Coast cyclogenesis associated with the southern branch of the westerlies may be responsible for a renewed peak in damming events in March.

As high pressure moves across northeastern United States, cold-air damming occurs when the easterly winds encounter the Appalachian mountains; this effects the weather conditions and precipitation patterns of the winter storms for the Atlantic coastal states. Richwien (1980) showed that cold-air damming enhances the intensity of the

cyclogenesis. There are other features that can be used to predict the intensity and duration of precipitation such as orographic features (Uccellini *et al*, 1988), thickness of atmospheric layers (Keeter *et al*, 1988) and temperature structure and distribution (Stewart *et al*, 1990).

Cold-air damming forms with relatively cold air near the surface and relatively warm air in the mid-levels of the atmosphere. There is a strong temperature dependence to the processes involved with precipitation type and amount (Stewart *et al*, 1990). The meteorological conditions necessary for ice pellets (or sleet) are determined by the details of the vertical profile of temperature or wet-bulb temperature (Penn, 1957). Precipitation forms in an ascending moist flow which is often described as overrunning a cooler layer of air at lower levels. The precipitation either forms in or falls through a layer of warm (above-freezing) air aloft. Precipitation emerging from this layer then falls through a surface-based cold (sub-freezing) layer in the form of ice pellets (Forbes *et al*, 1987).

The thickness values of atmospheric layers is used as a tool for predicting the precipitation type in winter storms. The 1000-500 mb thickness has long been used as a way to differentiate the precipitation type of winter storms (Wagner, 1957). The 1000-700 mb thickness provides a more detailed view of the thermal structure of the atmosphere. Koolwine (1975) first studied the partial thickness values of 1000-850 mb and 850-700 mb layers. He used these thicknesses to document warm air in the midlevels of the atmosphere and cold air at low levels. He found that freezing rain critical thickness values can be established. The 1000-850 mb thickness is less than 1314 m ($\pm$ 6 m). The 850-700 mb thickness is greater than 1539 m ($\pm$ 3 m). For convention, he used the values of 1310 m and 1540 m.

Bachand (1986) furthered this technique to include the precipitation type of ice pellets. He found that at a 850-700 mb thickness value greater than 1540 m, freezing rain would change to ice pellets. He also documented a critical thickness value at a 1000-850 mb thickness of 1290 m. Cantin and Bachand (1990) noted that in the presence of a low

level temperature inversion (generally ahead of a warm front), a 850-700 mb thickness greater than 1540 m implies temperature greater than freezing somewhere within that layer and that, similarly, a 1000-850 mb thickness greater than 1290 m, implies temperature greater than freezing below 850 mb. Conversely, in a low level temperature situation, a 1000-850 mb thickness less than 1290 m implies that all the layer 1000-850 mb is at a temperature below the freezing mark with a cold surface temperature. The latter indicates an ice pellet situation associated with a warm layer above 850 mb.

Keeter and Cline (1990) studied the critical thickness values for the Greensboro radiosonde station in North Carolina. They documented the 1000-700 mb critical thicknesses for different precipitation events. For an event of only frozen precipitation, the critical thickness value was less than 2825m; for an event of only liquid precipitation, the critical thickness value was greater than 2860m. For an event with a mixture of precipitation types that include a measurable amount of frozen precipitation, the critical thickness value was in a range from 2825m and 2845 m. For an event with a mixture of precipitation types with only a trace of frozen, the critical thickness value is in a range from 2845 m to 2860 m.

Keeter and Cline (1990) also determined partial critical thickness values. For an event with freezing rain and a measurable amount of frozen precipitation, the critical thickness values for 1000-850 mb is between 1280 m and 1290 m; for 850-700 mb, the critical thickness value is between 1540 m and 1560 m. For an event with freezing rain with only a trace of frozen precipitation, the 1000-850 mb critical thickness value is between 1290 m and 1310m; for 850-700 mb, the critical thickness value is between 1540 m and 1560 m.

Ice pellets (sleet) are defined as transparent or translucent pellets of ice, 5 mm or less in diameter; these form from the freezing of raindrops or refreezing of melted snowflakes when falling through a below-freezing layer of air near the earth's surface. Snow falls into the elevated warm layer and partially melts before entering the lower cool

layer. This partial melting produces an ice crystal surrounded by liquid water. As this combination falls into the below-freezing layer, it begins to refreeze immediately, due to the presence of the ice crystal. This results in ice pellets at the surface. The key difference between freezing rain and ice pellets is the degree of melting that the snow undergoes in the elevated warm layer. If the maximum temperature in the warm layer exceeds 3 to 4 ^{o}C, snowflakes melt completely to liquid resulting in rain or freezing rain. If the maximum temperature in the warm layer is less than 1 ^{o}C, only partial melting occurs, followed by complete refreezing in the cool layer, resulting in snow at the surface. Warm layers with maximum temperatures between 1 and 3 ^{o}C have a mixture of partially melted and completely melted snowflakes. This results in ice pellets, or more commonly a mixture of snow, rain (or freezing rain), and ice pellets (McNulty, 1988).

Michaels (1991) developed a climatology of sleet and freezing rain for Virginia. He showed that these events are most common along the foothills of central Virginia, where a shallow layer of cold air is trapped along the eastern side of the Appalachians and warm overrunning air from the ocean produces conditions for the formation of freezing and frozen precipitation. The present research will first analyze in detail a major sleet storm over the southeast. This specific event will then be put in context by comparing it with a typical situation as determined from a forty-one year climatology (1949/50-1989/90) of sleet producing storms.

1.2 GOALS/OBJECTIVES

The objectives of the case study are:

(1) Characterize the synoptic and frontal scale circulations that lead to the prolonged mixed precipitation event over North Carolina.

(2) Specifically investigate the interaction of synoptic flows and terrain, and its subsequent impact on the evolution and movement of fronts and mixed precipitation areas.

(3) Document the evolution and extent of the mixed precipitation areas associated with the storm.

1.3 Synoptic Analysis

Friday, February 13, 1987 provided the first clues to the synoptic situation of the case study; a low pressure center formed in the panhandle of Texas. This low gradually moved eastward and, by 0000 UTC on 16 February, was located in northwest Mississippi (Fig. 3.A). A cold front extended southward through central Louisiana and into the Gulf of Mexico. A 996 mb isobar encloses the area of the surface low and cold front. A strong area of surface convergence can be found in eastern Mississippi ahead of the cold front. A stationary front extended through central Alabama and Georgia and into the Atlantic ocean. Another area of strong surface convergence can be found in eastern Alabama and eastern Georgia and into the Atlantic ocean corresponding to the location of the stationary front. A high pressure center located north of the Great Lakes produced anticyclonic circulation over the northeastern region of the U.S. Cold-air damming was established along the east coast as the easterly winds along the southern side of the high pressure cell encountered the Appalachian mountains. Ageostrophic winds dominated the southeast. The cold-air damming will gradually strengthen and force the stationary front southward.

The 0000 UTC Infrared satellite photo (Fig. 3.B) shows cloudiness over most of the southeast. There is a clear area over Mississippi which is ahead of the surface front and behind a cold front aloft (CFA). Businger *et al* (1991) use this term to denote cold-frontal zones whose bases are above the surface in the lower or middle troposphere. In some cases the CFA may have its origin as an upper-level front of the type discussed by Reed (1955) and Keyser and Shapiro (1986). Evidence for the presence of a CFA can be seen in the temperature analysis and in the pattern of cold advection and convergence at 850 mb and at 700 mb. The highest clouds can be seen in southern Alabama associated

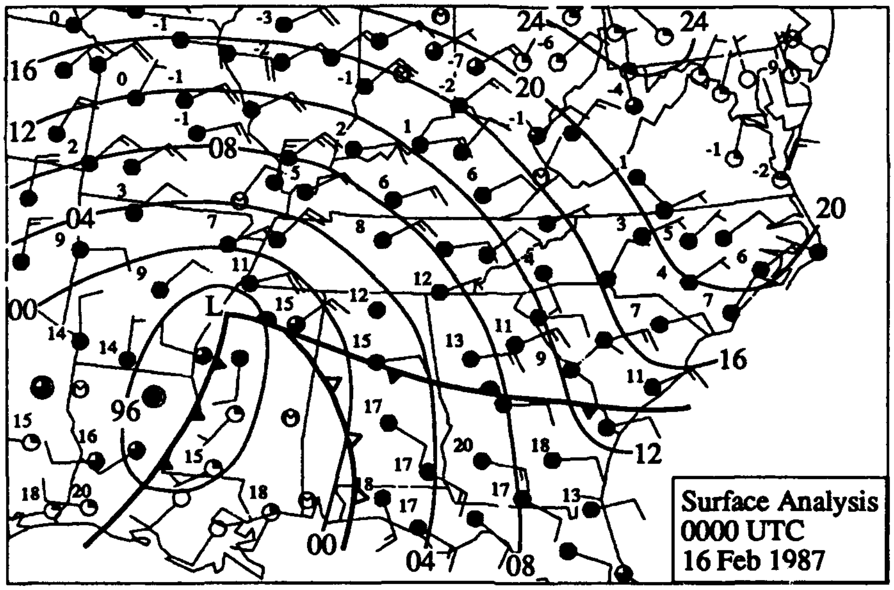

Fig. 3.A: Synoptic surface analysis for 0000 UTC 16 Feb, 1987. Shown are isobars in 4 mb intervals and temperature in degrees C.

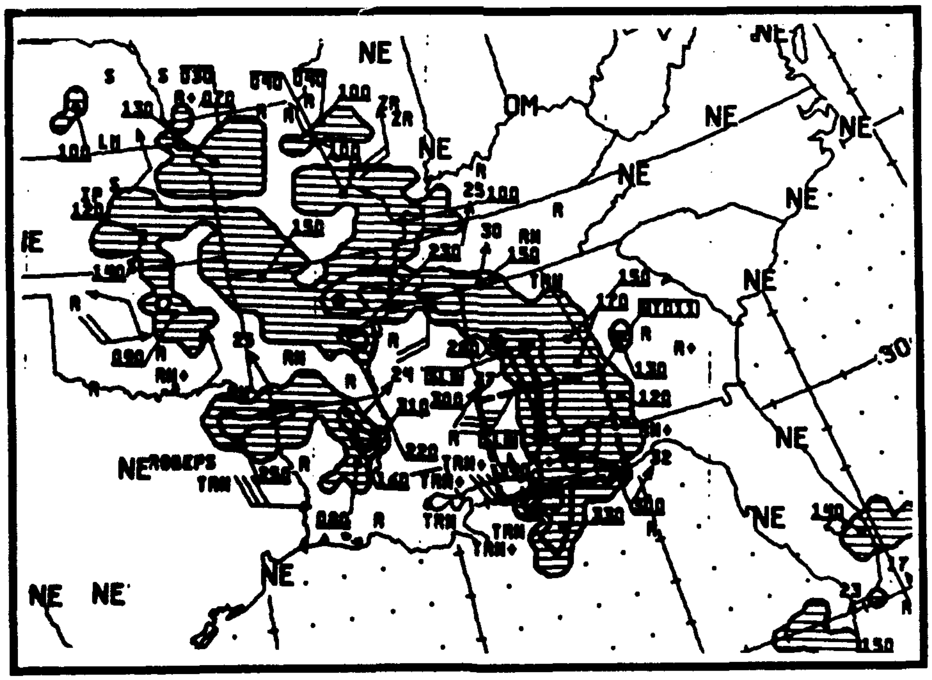

Fig. 3.C: The radar summary for 0035 UTC 16 Feb, 1987

Fig. 3.B: Infrared satellite photo for 0000 UTC 16 Feb, 1987

with a area of convection ahead of the CFA. This convection will infuse moisture into the southwest airstream in the mid-troposphere. The 0035 UTC radar (Fig. 3.C) shows scattered echoes across the southeast with maximum tops of 39,000 feet associated with a watch box for severe thunderstorms in southern Alabama. The echoes will gradually move to the northeast and into the Atlantic ocean.

An area of freezing and frozen precipitation can be found in central Missouri and Kansas (Fig. 3.D) with the 0 ^{o}C isotherm stretching from Kansas to North Carolina. This band of freezing/frozen precipitation will gradually progress eastward as rain falls into the dry air ahead of the band and cools the atmosphere due to evaporative cooling. Surface relative humidities of 90 % or greater are located throughout the southeast. The surface dew point depressions (Fig. 3.E) show a tongue of dry air, with dew point depressions greater than 10 ^{o}C, pushing into the Ohio River Valley from the Northeast. The contour of 3 ^{o}C dew point depression borders the freezing/frozen precipitation band to the north; the 0 ^{o}C isotherm borders the south.The tight gradient of the contours in Tennessee shows the transition from moist air to dry air.

At 850 mb (Fig. 4.A), a strong closed low is centered over southern Arkansas; this system will move very slowly over the southeast and the cyclonic circulation will bring warm moist air from the Gulf of Mexico into the southeast. The high over the Great Lakes is not present at 850 mb suggesting that it is a shallow surface feature. At 500 mb (Fig 4.B), a low is centered over southwest Arkansas suggesting strong mid-level support for the surface low in Mississippi. The lows slope westerly with height. A jet is located at 500 mb on the south side of the low with the strongest winds in eastern Louisiana. The left front exit region of the jet is located over the Carolinas providing upward vertical motion.

At 0600 UTC (Fig. 5.A), the cold-air damming has strengthened as evidenced by the 1024 mb contour dipping into southern Virginia. Ageostrophic winds

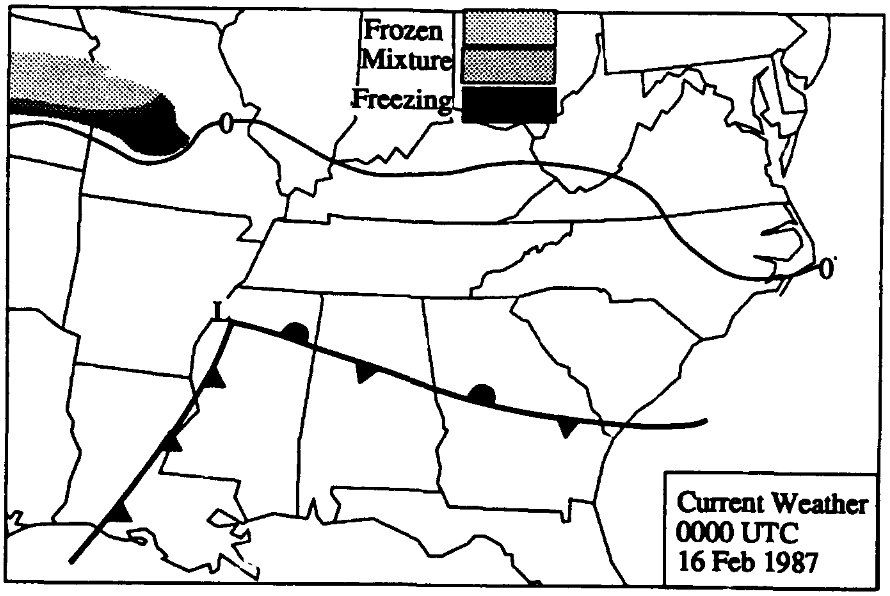

Fig. 3.D: The current weather conditions for 0000 UTC 16 Feb, 1987. Shown is freezing, mixture and frozen precipitation with the 0 degree isotherm.

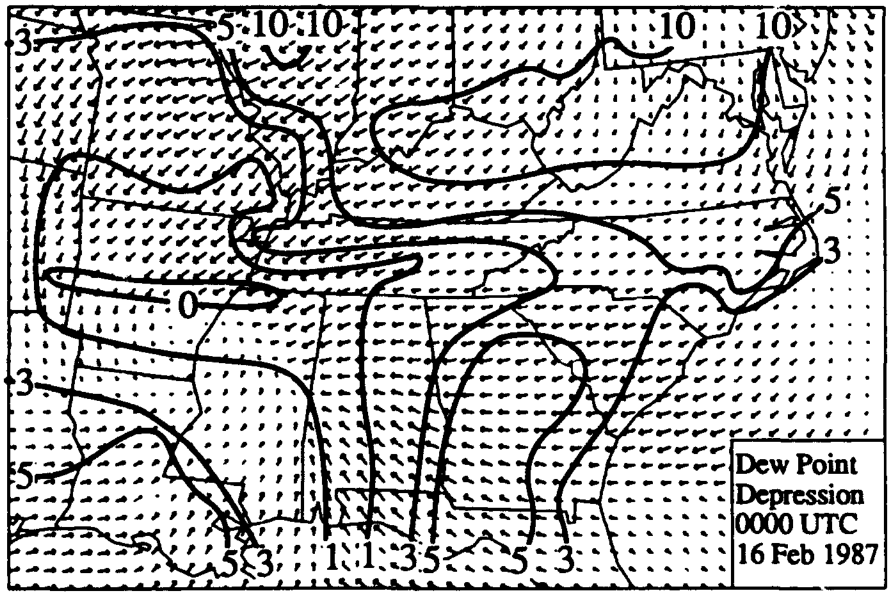

Fig. 3.E: Dew point depression analysis for 0000 UTC 16 Feb 1987. Shown are isopleths of dew point depression in degrees C with the wind vectors.

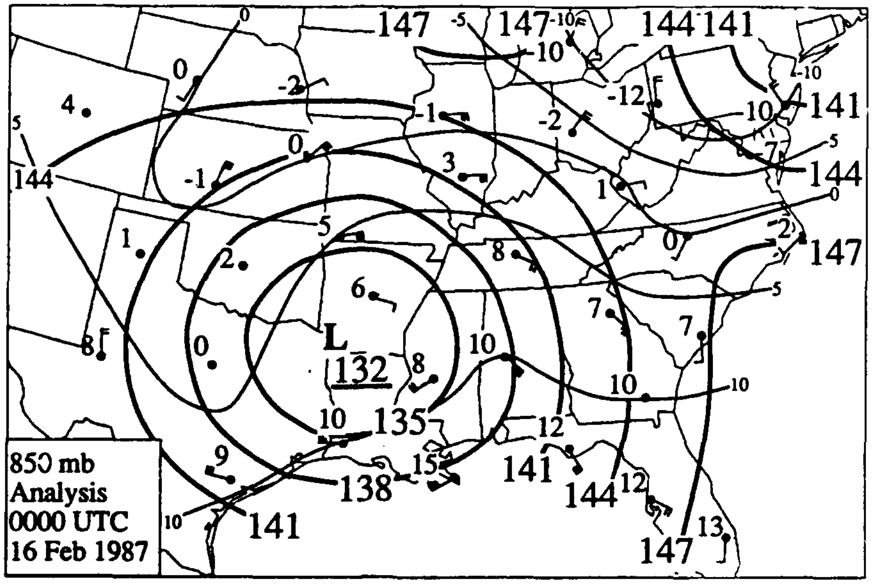

Fig. 4.A: 850 mb analysis for 0000 UTC 16 Feb 1987. Thick lines are 30 m height contours. Thin lines are 5 degree isotherms.

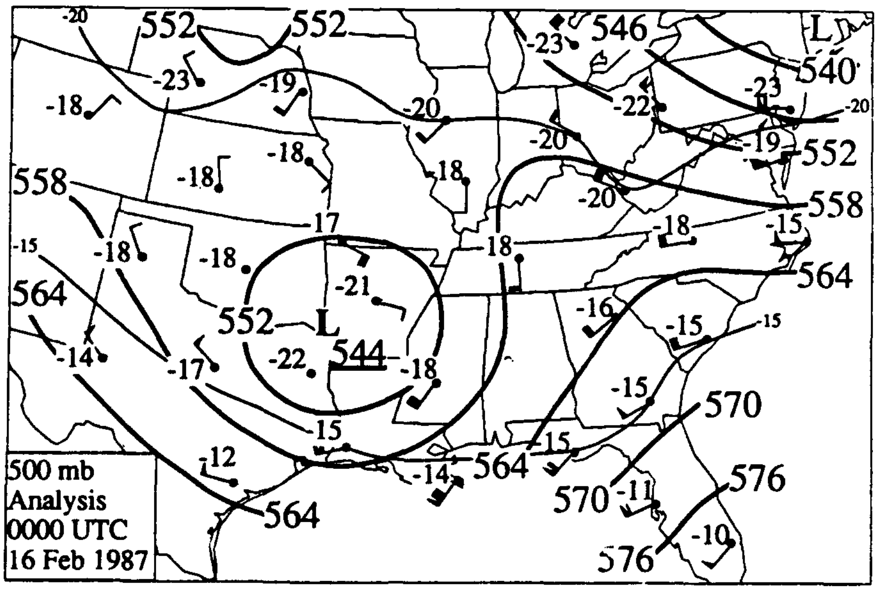

Fig. 4.B: 500 mb analysis for 0000 UTC 16 Feb 1987. Thick lines are 60 m height contours. Thin lines are 5 degree isotherms.

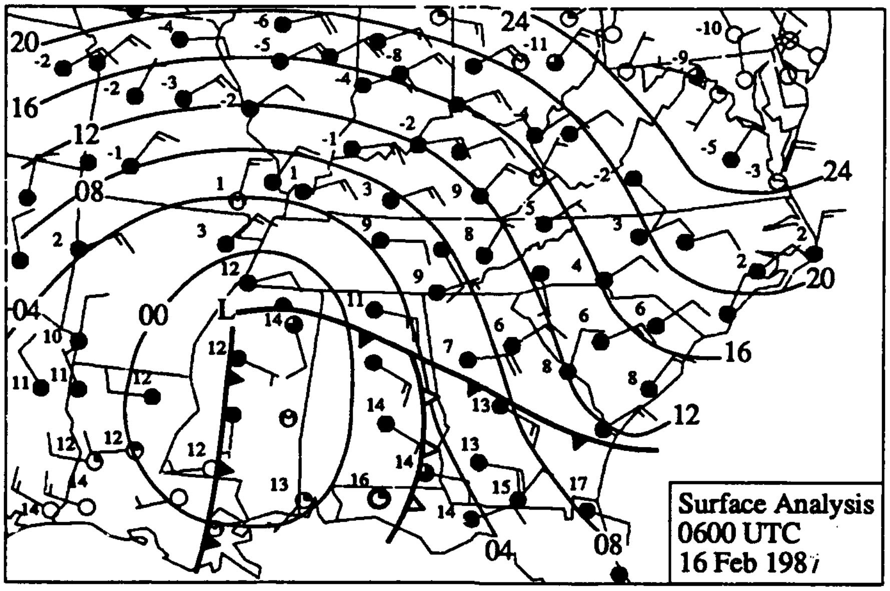

Fig. 5.A: Synoptic surface analysis for 0600 UTC 16 Feb, 1987. Shown are isobars in 4 mb intervals and temperature in degrees C.

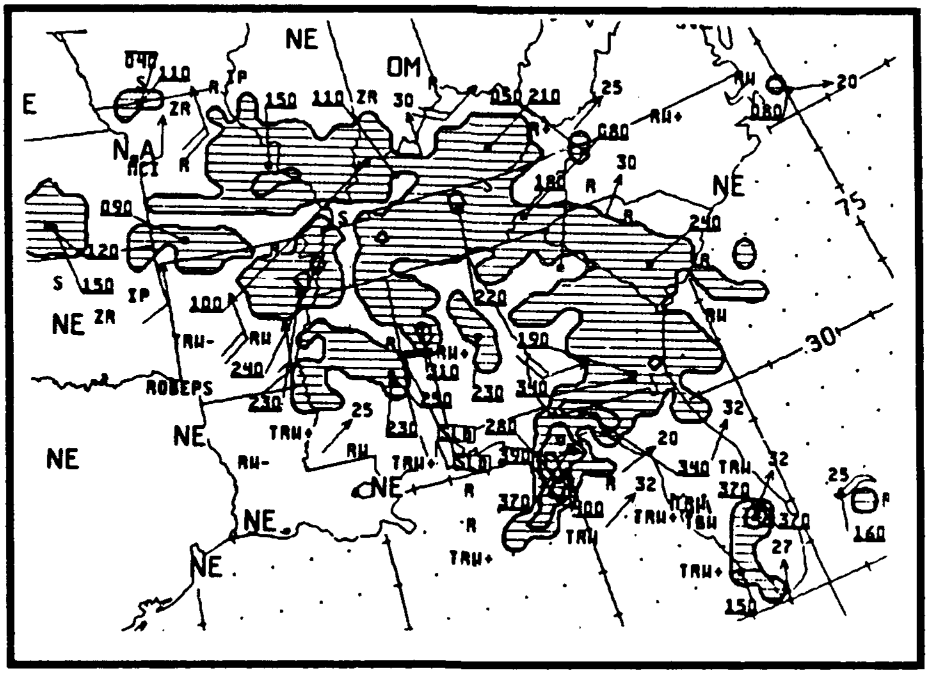

Fig. 5.B: The radar summary for 0635 UTC 16 Feb, 1987

dominate the southeast. The stationary front is gradually being pushed southward by the strength of the cold-air damming and has transformed into a cold front. The low continues to fill with the area under the 1000 mb isobar gradually decreasing. The 0635 UTC radar (Fig. 5.B) shows a wide area of scattered echoes in the Atlantic coastal region with the convective area associated with the CFA having maximum tops reaching 40,000 feet and located over the panhandle of Florida. The freezing rain has spread into northern Kentucky with sleet being reported in Illinois (Fig. 5.C). The dewpoint depression pattern (Fig. 5.D) show the rapid transition from dry to moist air especially in the tight gradient of the 1 and 5 ^{o}C dew point depression isopleths.

At 1200 UTC (Fig. 6.A), the cold-air damming region has strengthened evident by the tightening of the isobars east of the Appalachian mountains. Strong ageostrophic winds over the Carolinas and Georgia push the cold front even farther south. The surface low continues to fill. Pronounced surface convergence is located in the northern portions of Mississippi and Alabama as well as off the coast of Georgia and western Florida. The 1200 UTC IR satellite photo (Fig. 6.B) shows that the highest clouds are off the coasts of the Carolinas and that most of the activity is to the north and east of the CFA located in southern Georgia. A wide clearing area is located in the southern sections of Louisiana, Mississippi, and Alabama associated with the cold air behind the CFA. The 1235 UTC radar (Fig. 6.C) shows that there are no echoes associated with the cold front found in Louisiana suggesting that it is a dry front. The convection in Florida, ahead of the CFA, has intensified. the maximum tops rise to 45,000 feet in the watch box.

A thin band of freezing rain stretches from Kentucky into northern South Carolina (Fig. 6.D) ahead of the dry air that is over North Carolina. Moist air continues to dominate the southeast and pushes northeastward into the dry air in the Ohio River valley. The dew point depressions (Fig. 6.E) show that a tongue of dry air has

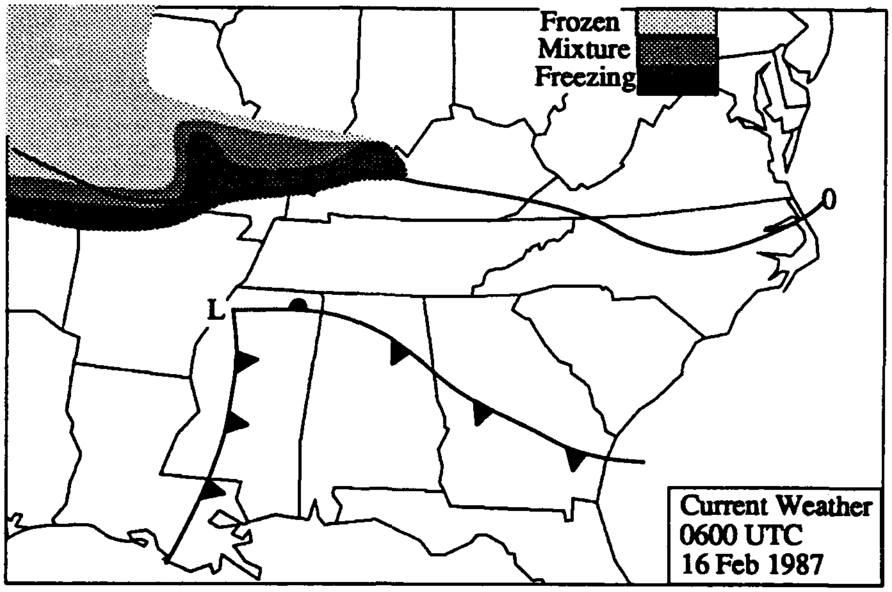

Fig. 5.C: The current weather conditions for 0600 UTC 16 Feb, 1987. Shown is freezing, mixture and frozen precipitation with the 0 degree isotherm.

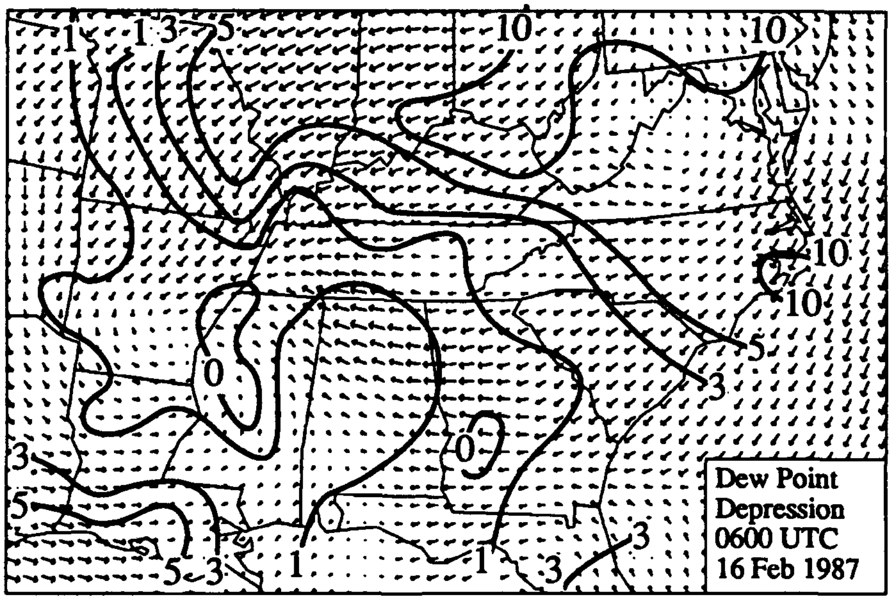

Fig. 5.D: Dew point depression analysis for 0600 UTC 16 Feb, 1987. Shown are dew point depression isopleths in degrees C with wind vectors.

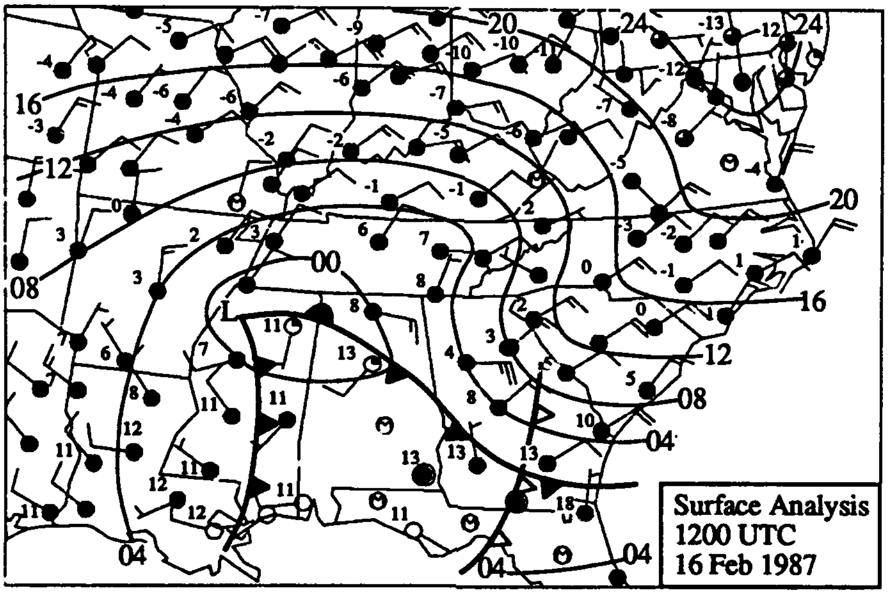

Fig. 6.A: Synoptic surface analysis for 1200 UTC 16 Feb, 1987. Shown are isobars in 4 mb intervals and temperature in degrees C.

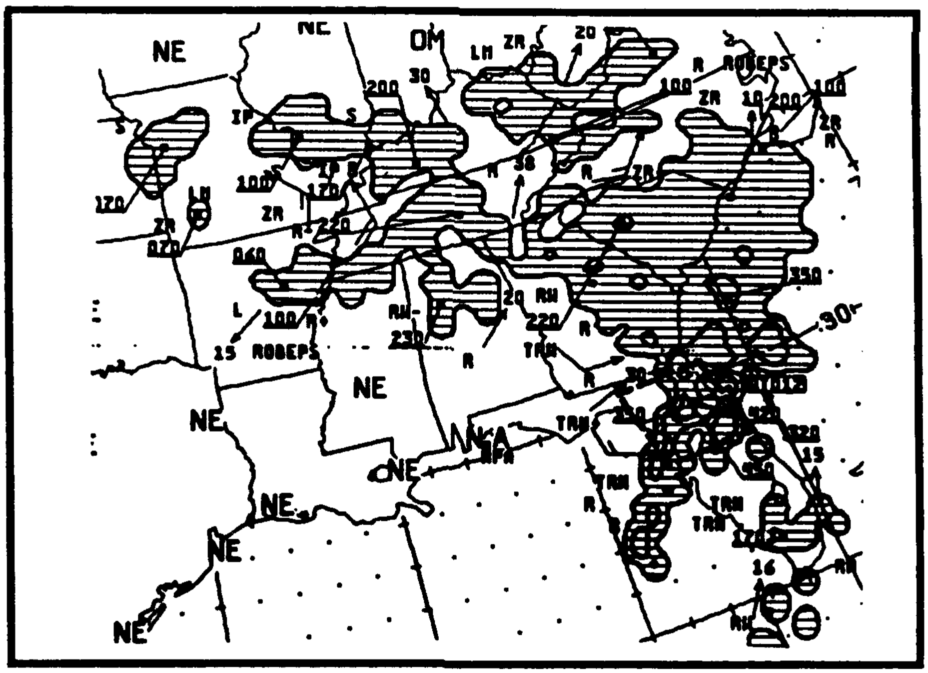

Fig. 6.C The radar summary for 1235 UTC 16 Feb, 1987

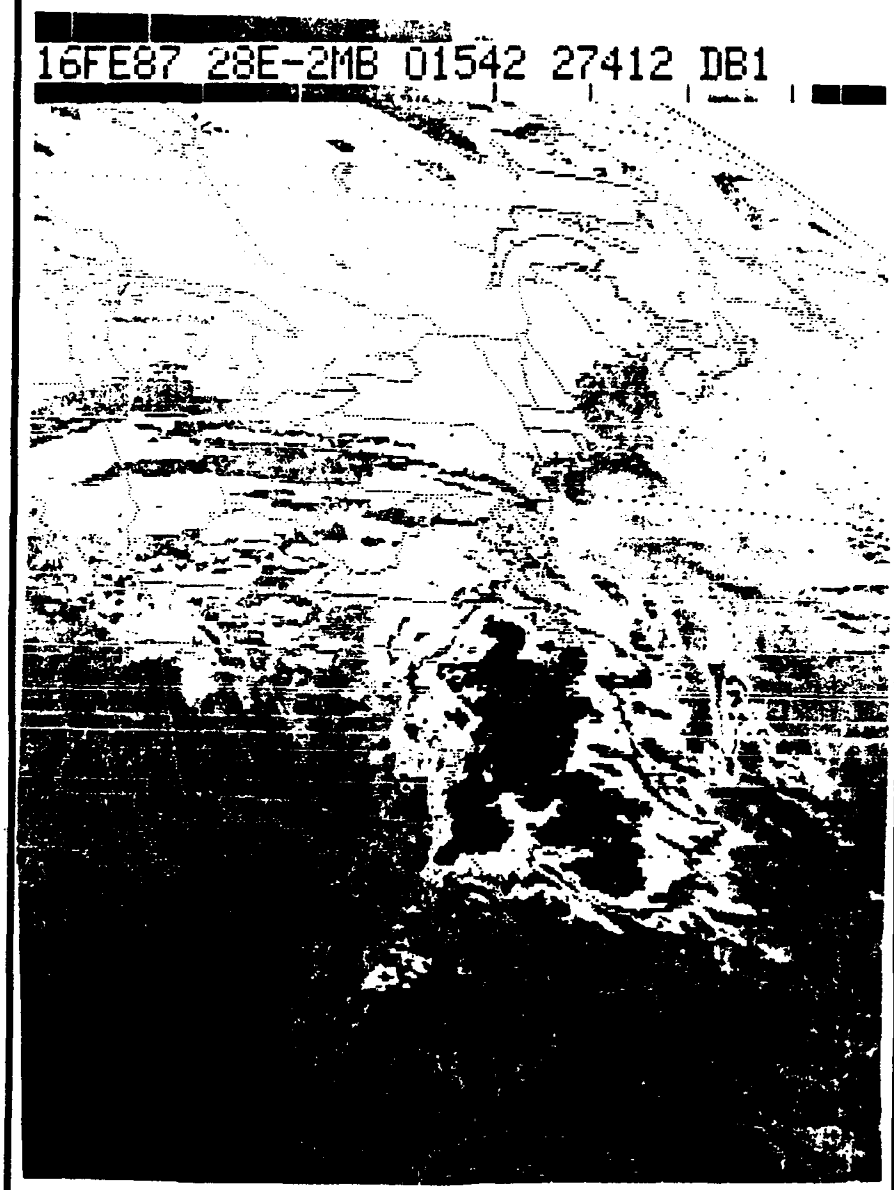

Fig. 6.B: Infrared satellite photo for 1200 UTC 16 Feb, 1987

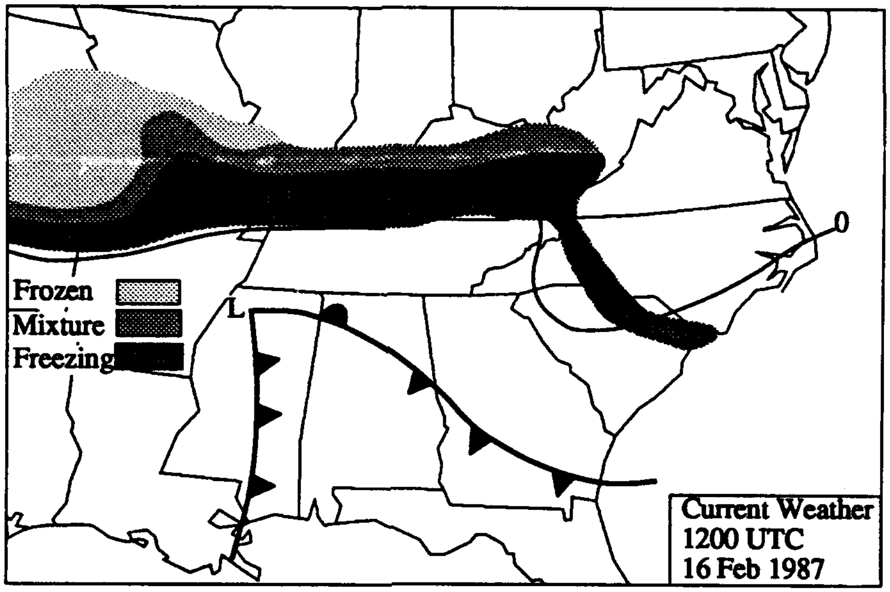

Fig. 6.D: The current weather conditions for 1200 UTC 16 Feb, 1987. Shown is freezing, mixture and frozen precipitation with the 0 degree isotherm.

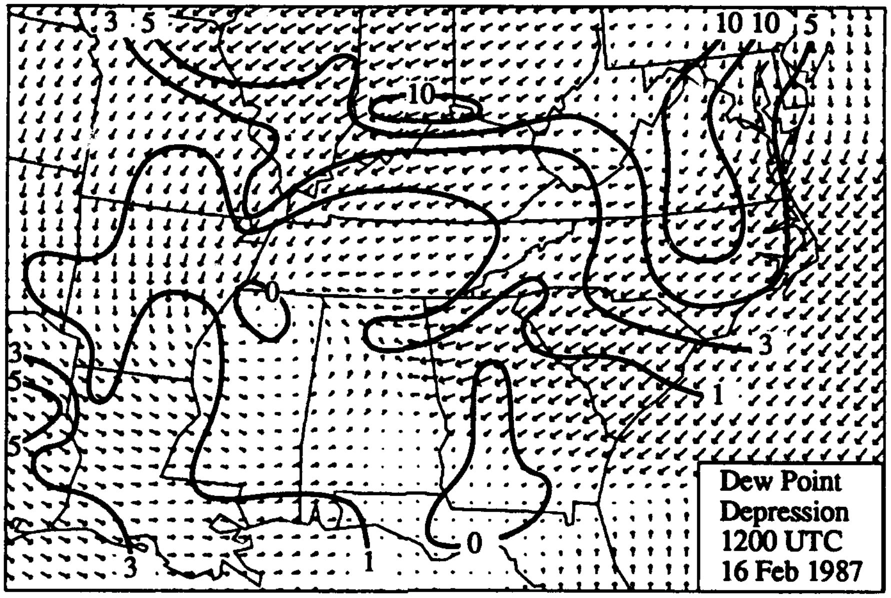

Fig. 6.E: Dew point depression analysis for 1200 UTC 16 Feb,1987. Shown are isopleths of dew point depression in degrees C with wind vectors.

extended through Virginia into North Carolina. This dry air borders northern side of the freezing rain band.

At 850 mb (Fig. 7.A), the low has filled slightly and moved very slowly eastward to northern Mississippi above the surface low. The cyclonic circulation provides warm air advection to the southeast and cold air advection behind the CFA along the Gulf of Mexico. A trough exists in southern Georgia reflecting the surface cold front. At 500 mb (Fig. 7.B), the low has filled slightly and moved to northern Mississippi. A jet is located over northern Florida with the left front exit region over North Carolina.

At 1800 UTC (Fig. 8.A), the surface low (low1) has moved to north central Mississippi and the cold front has weakened to a pressure trough located over western Alabama. The low continues to fill to a central pressure of about 1002 mb. There is a suggestion of a secondary cyclogenesis over southern Georgia with the presence of a secondary surface low (low2). A strong area of surface convergence is located in northwest Alabama, northeastern Mississippi, and western Tennessee; an additional area is located across southern Georgia. These areas correspond to the surface fronts. The cold-air damming weakened slightly as indicated by the 1020 mb isobar moving northward into Virginia from North Carolina. The 1835 UTC radar (Fig. 8.B) shows a small area of echoes centered over North Carolina with imbedded thunderstorms with maximum tops to 22,000 feet. A line of echoes is located over Florida with maximum tops dropping to 38,000 feet suggesting a weakening of the convection in the thunderstorms ahead of the CFA. The freezing/frozen band of precipitation (Fig. 8.C) extends from Kansas through Kentucky to the Carolina coast. Falling precipitation has moistened the air over the Carolinas where dew point depressions have decreased to less than 3 ^{o}C. Little additional evaporative cooling can be expected (Fig. 8.D).

Six hours later at 0000 UTC on 17 February, 1987 (Fig. 9.A), the closed low in Mississippi (low1) has filled and a trough takes its place in central Alabama. The cold-air damming seems to be weakening as suggested by a decreasing pressure gradient

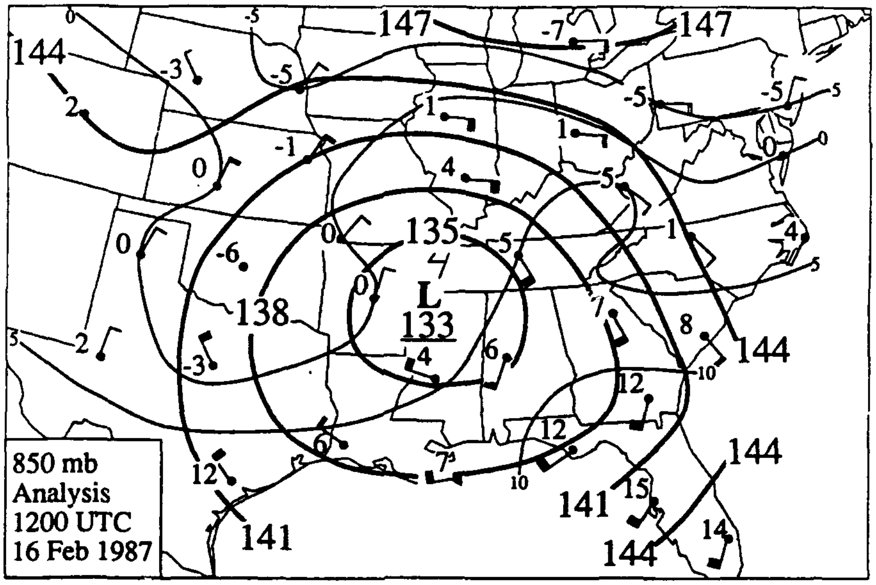

Fig. 7.A: 850 mb analysis for 1200 UTC 16 Feb 1987. Thick lines are 30 m height contours. The thin lines are 5 degree isotherms.

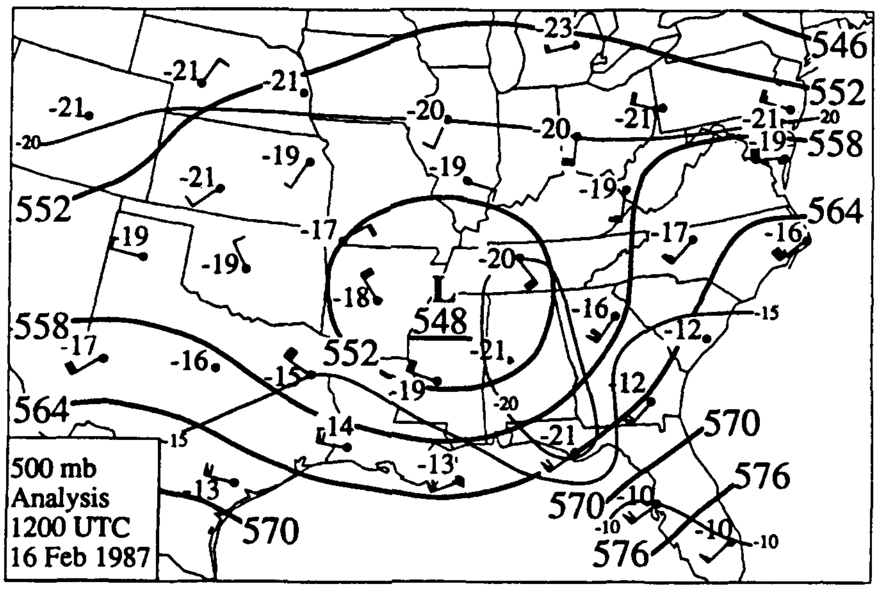

Fig. 7.B: 500 mb analysis for 1200 UTC 16 Feb 1987. Thick lines are 60 m height contours. The thin lines are 5 degree isotherms.

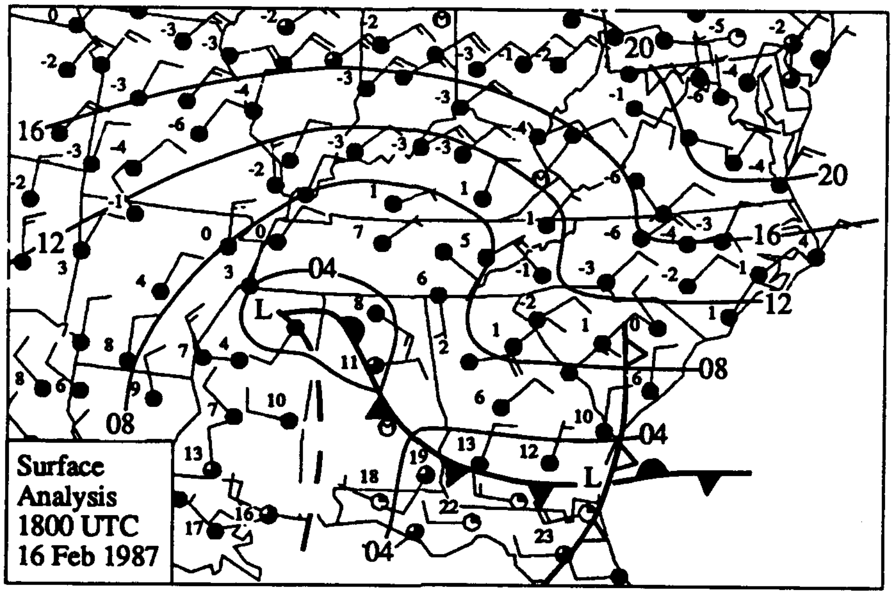

Fig. 8.A: Synoptic surface analysis for 1800 UTC 16 Feb, 1987. Shown are isobars in 4 mb intervals and temperature in degrees C.

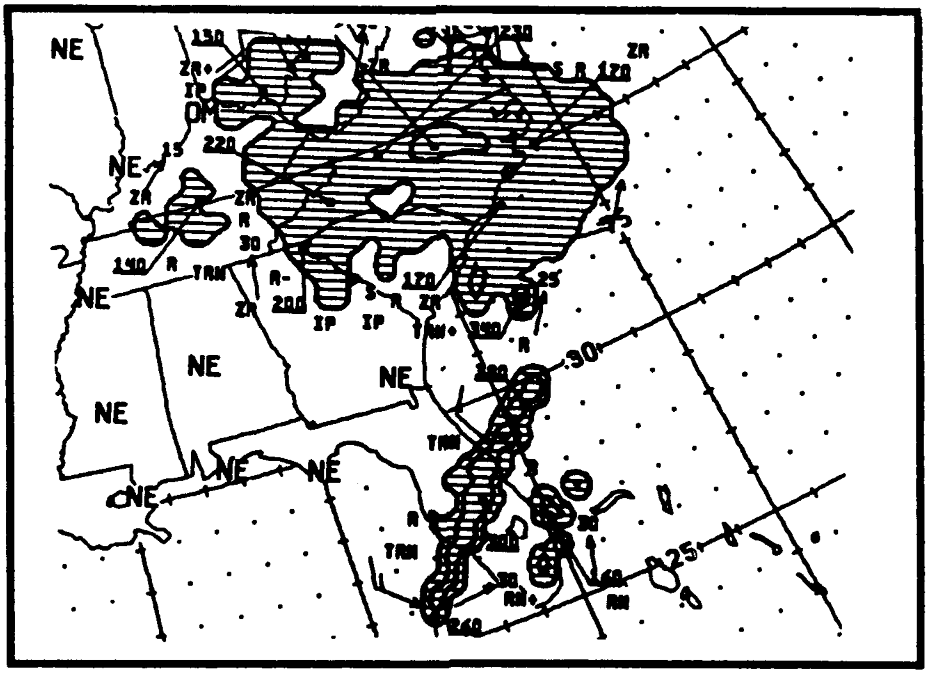

Fig. 8.B: The radar summary for 1835 UTC 16 Feb, 1987

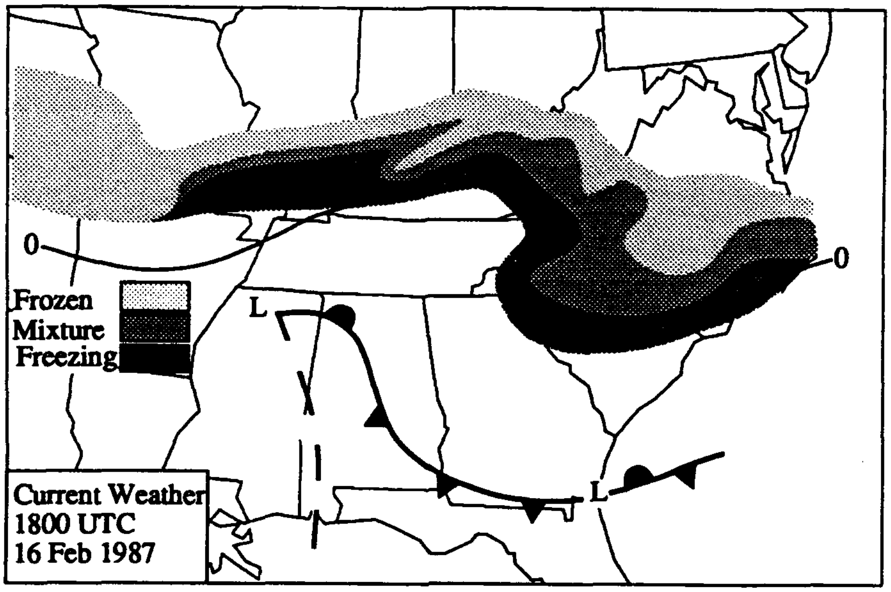

Fig. 8.C: The current weather conditions for 1800 UTC 16 Feb, 1987. Shown is freezing, mixture and frozen precipitation with the 0 degree isotherm.

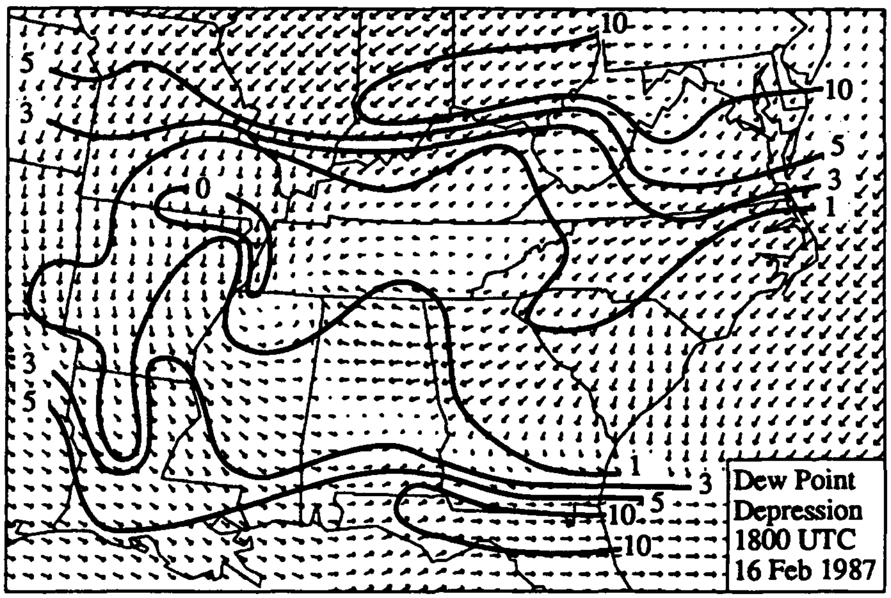

Fig. 8.D: Dew point depression analysis for 1800 UTC 16 Feb, 1987. Shown are dew point depression isopleths in degrees C with wind vectors.

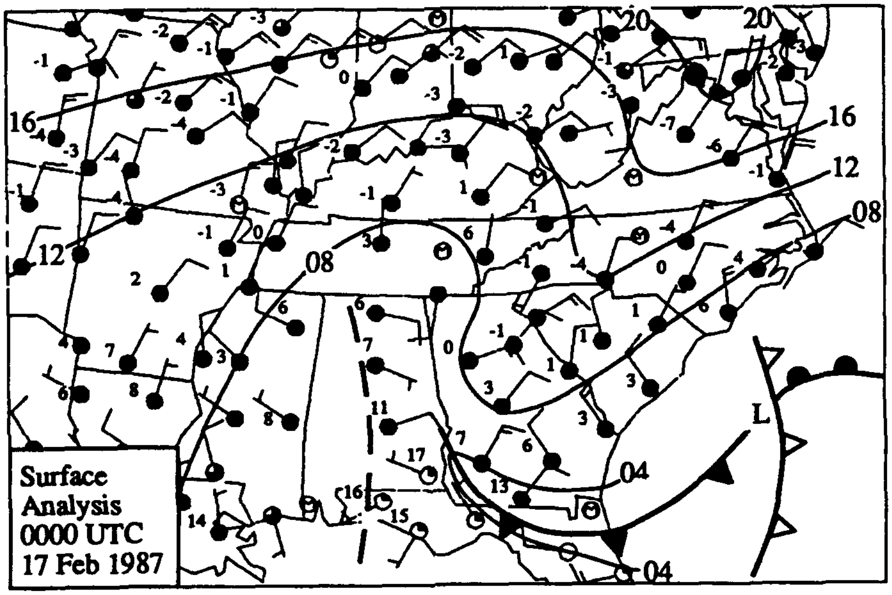

Fig. 9.A: Synoptic surface analysis for 0000 UTC 17 Feb, 1987. Shown are isobars in 4 mb intervals and temperature in degrees C.

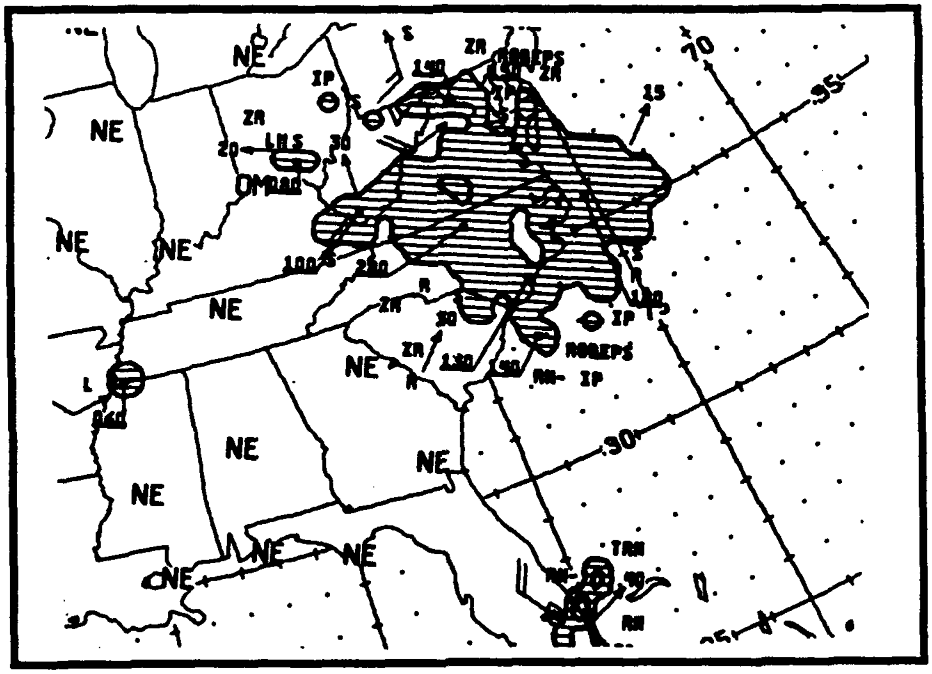

Fig. 9.C: The radar summary for 0035 UTC 17 Feb, 1987

in the high pressure ridge. The intensifying low off the Georgia-South Carolina coast (low2) continues to pull cooler air southeastward as the front slips into northern Florida. Surface convergence continues along the active part of the front. The 2131 UTC Visible satellite photo (Fig. 9.B) from 16 February shows the cloud formations over the southeast. High clouds are noted over Missouri, Kentucky, and the Carolinas indicating the possibility of imbedded thunderstorms. A wide clear area can be found over Florida ahead of the surface cold front and behind the CFA. Ahead of the CFA, a line of convective clouds occur over southern Florida. The 0035 UTC radar (Fig. 9.C) shows a small area of echoes over Florida with maximum tops at 40,000 feet. An additional area of echoes can be found over North Carolina and Virginia with 28,000 feet maximum tops. The latter are evidently imbedded convective clouds as thunder and lightning accompanied the sleet event.

A finger of freezing rain has extended into Georgia and frozen precipitation covers the central area of North Carolina and virtually all of Virginia (Fig. 9.D). The frozen precipitation is primarily sleet as little accumulations of snow were reported. Moist air still covers most of the southeast (Fig. 9.E). The dry air in Florida is ahead of the surface cold front and in the clear area shown by the satellite photo behind the CFA.

At 850 mb (Fig. 10.A), the low continues to fill and is centered over Tennessee. A pronounced trough associated with the offshore cyclogenesis extends eastward. An eastward jet is located over southern Florida with an additional westward jet over North Carolina. Cold air advection exists along the Gulf of Mexico behind the CFA. At 500 mb (Fig. 10.B), the low continues to fill and is centered over Kentucky. A long-wave trough stretches over Texas and southwesterly flow prevails over the southeast.

At 0600 UTC (Fig. 11.A), the dominant surface low (low2) is located off the coast of central North Carolina. The pressure continues to rise throughout the southeast. Areas of convergence are located over western Alabama associated with the weakening trough and in eastern North Carolina. The 0635 UTC radar (Fig. 11.B) shows an area of

Fig. 9.B: Visible satellite photo for 2131 UTC 16 Feb, 1987

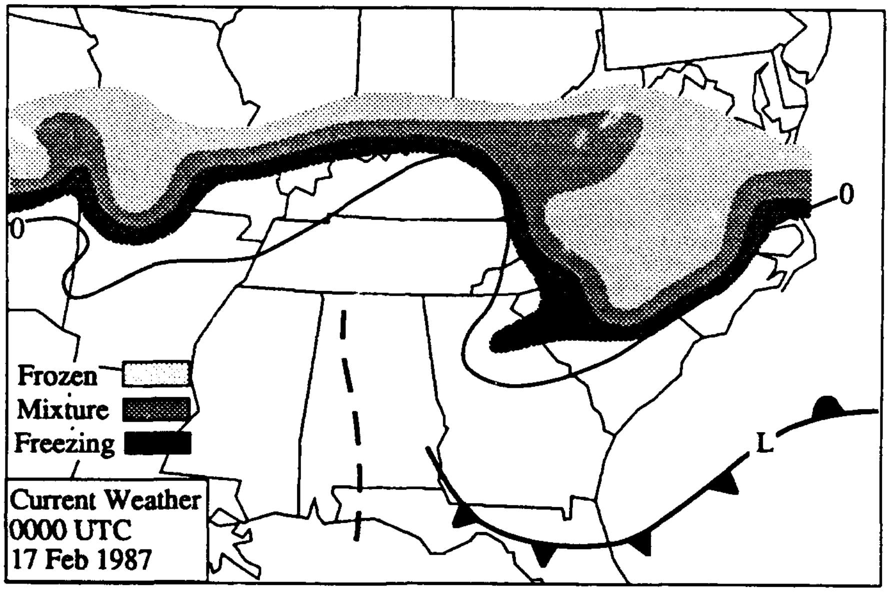

Fig. 9.D: The current weather conditions for 0000 UTC 17 Feb, 1987. Shown is freezing, mixture and frozen precipitation and the 0 degree isotherm.

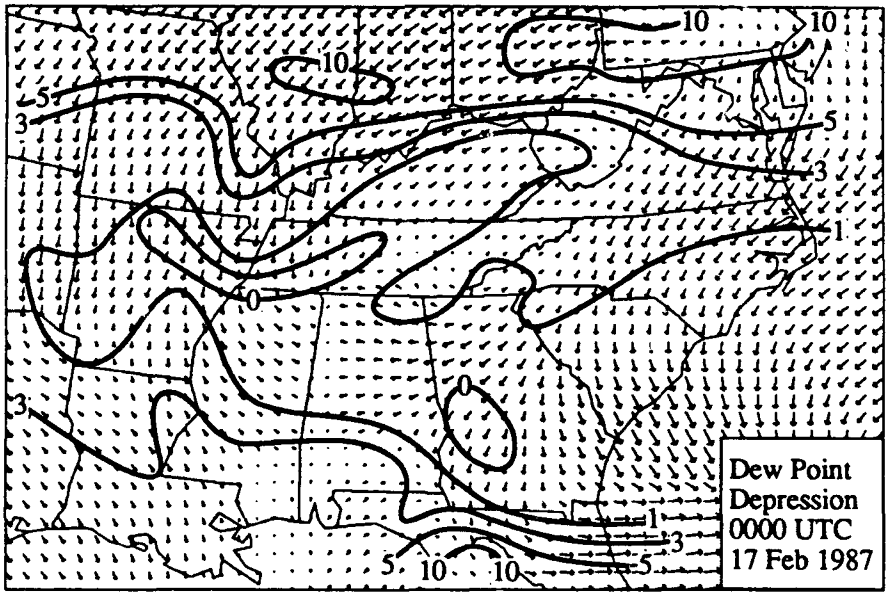

Fig. 9.E: Dew point depression analysis for 0000 UTC 17 Feb, 1987. Shown are dew point depression isopleths in degrees C with wind vectors.

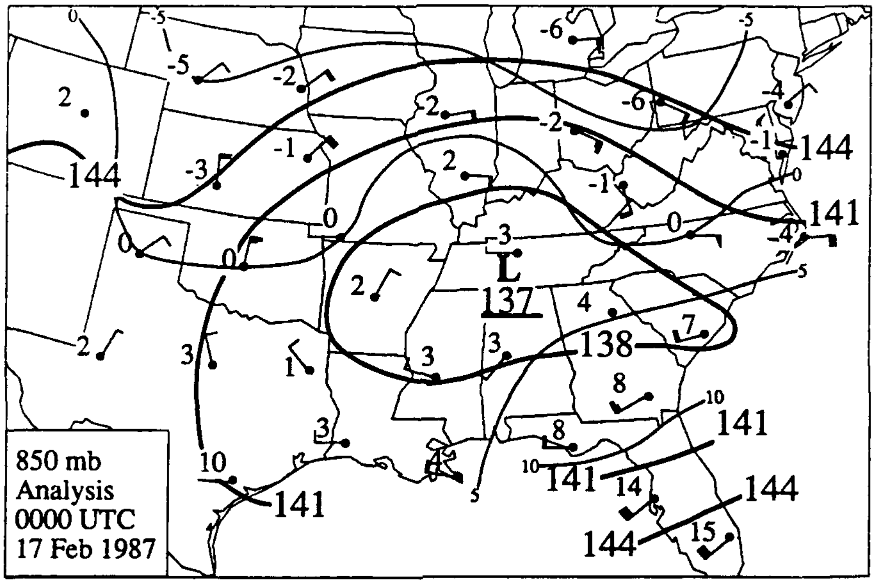

Fig. 10.A: 850 mb analysis for 0000 UTC 17 Feb 1987. Thick lines are 30 m contours. The thin lines are 5 degree isotherms

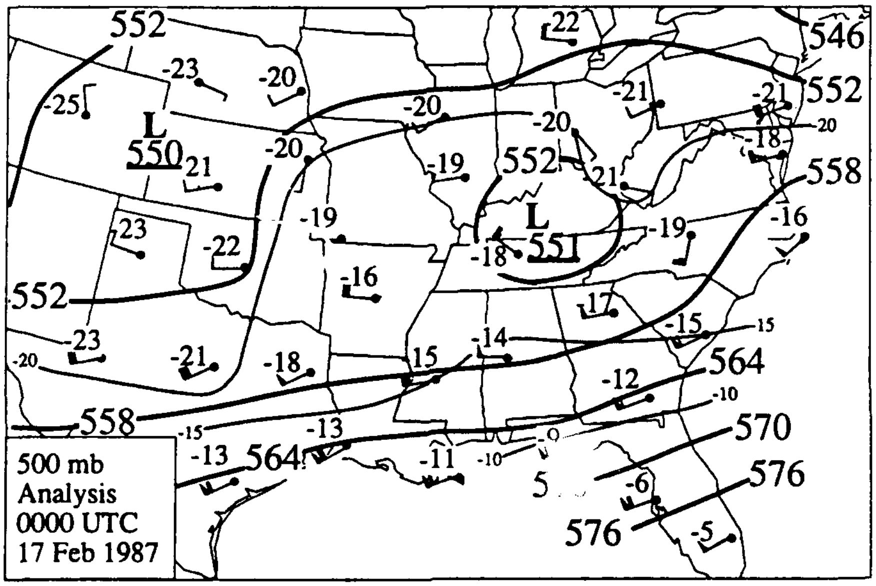

Fig. 10.B 500 mb analysis for 0000 UTC 17 Feb 1987. Thick lines are 60 m height contours. The thin lines are 5 degree isotherms.

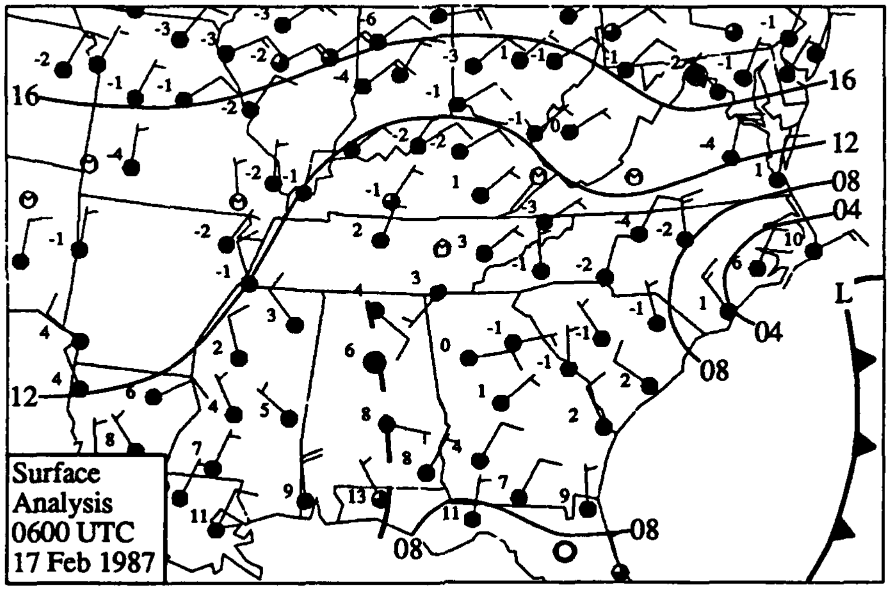

Fig. 11.A: Synoptic surface analysis for 0600 UTC 17 Feb 1987. Shown are isobars in 4 mb intervals and temperature in degrees C.

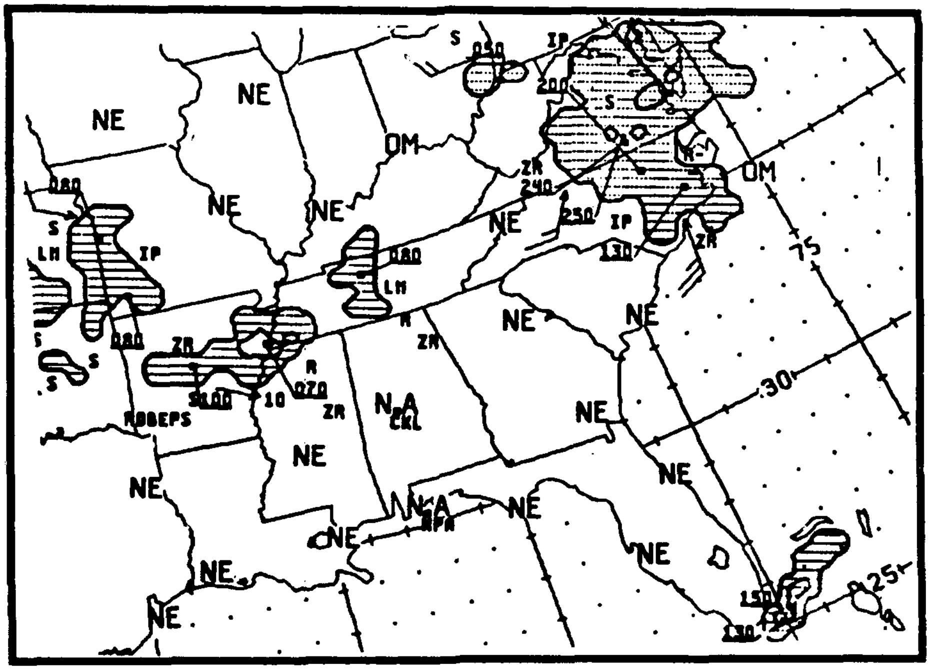

Fig. 11.B: The radar summary for 0635 UTC 17 Feb, 1987

echoes centered over Virginia, moving to the northeast, with maximum tops to 25,000 feet. Weaker echoes are found in Florida, Arkansas, and Tennessee. The southern border of the freezing/frozen precipitation band has receded northward to the northern half of North Carolina (Fig. 11.C). The precipitation is mainly frozen with a narrow band of freezing and mixed precipitation. The air over the Carolinas is approaching saturation with dew point depression equalling approximately zero (Fig. 11.D). The dry air covers Pennsylvania and extends into Ohio.

At 1200 UTC (Fig. 12.A), the 1012 mb isobar extends into southeastern Georgia along the Appalachian mountains. Northerly flow over Virginia and the Carolinas is now maintained by the offshore cyclone. Surface convergence continues with the Tennessee-Alabama trough. The 1201 UTC IR satellite photo (Fig. 12.B) shows that most of the activity has moved off the coast of Virginia as the surface cold front and CFA moves offshore into the Atlantic ocean. The 1235 UTC radar (Fig. 12.C) shows a small area of echoes over Virginia with 21,000 feet maximum tops.

The freezing/frozen precipitation band has moved slightly southward to southern North Carolina (Fig. 12.D). The 0 ^{o}C isotherm has receded northward to northeast Georgia. Moist air covers most of the southeast with dry air found in western Pennsylvania and eastern Ohio (Fig. 12.E).

At 850 mb (Fig. 13.A), a stronger low has formed off the coast of North Carolina with a weaker low centered over western Tennessee. A short-wave trough exists over eastern Texas with another offshore along the coast of the Atlantic ocean. At 500 mb (Fig. 13.B), the southwest flow dominates the southeast states. A jet is located over northern Florida and along the coasts of the Carolinas. The strongest winds occur over central Georgia. A low exists over Oklahoma with a high existing over Missouri. A short-wave trough exists off the coasts of the Carolinas.

Sleet was last reported in the Southeast at 1500 UTC and the synoptic situation became a snow event. A closed low formed over Tennessee as the cold-air damming

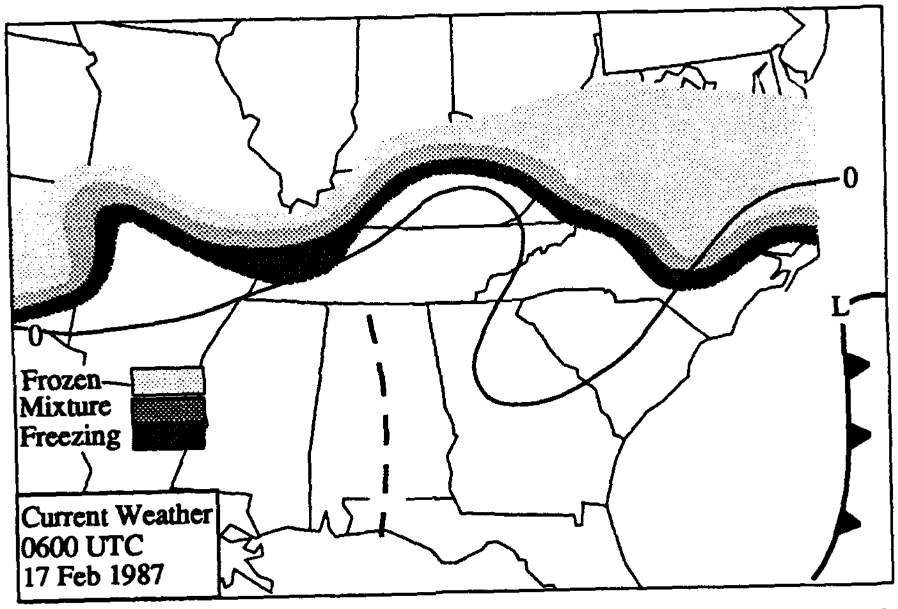

Fig. 11.C: The current weather conditions for 0600 UTC 17 Feb, 1987. Shown is freezing, mixture and frozen precipitation with the 0 degree isotherm.

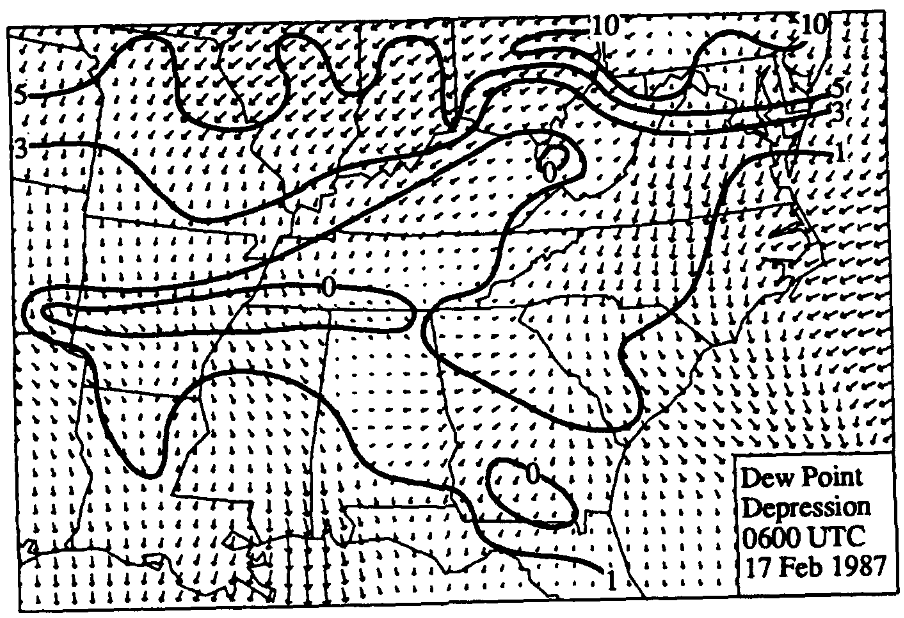

Fig. 11.D: Dew point depression analysis for 0600 UTC 17 Feb, 1987. Shown are dew point depression isopleths in degrees C and wind vectors.

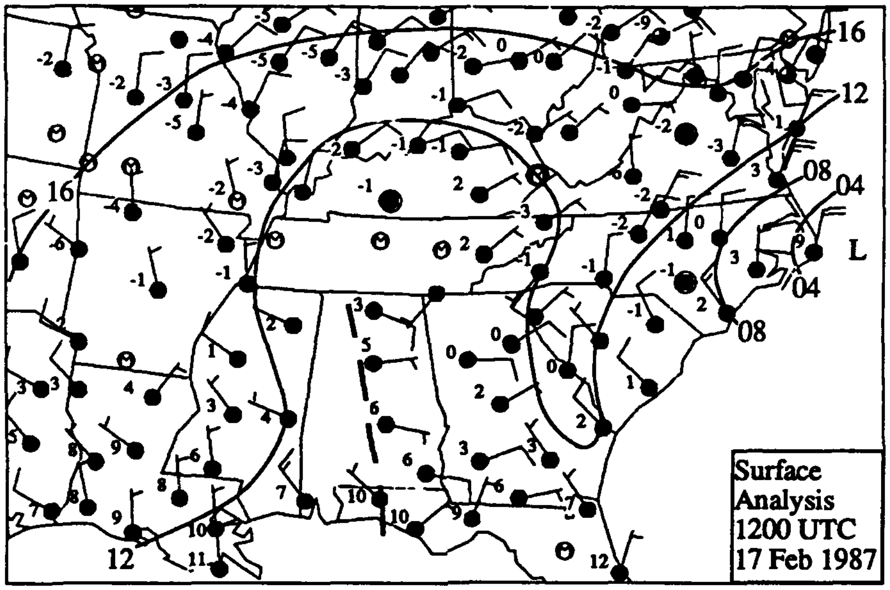

Fig. 12.A: Synoptic surface analysis for 1200 UTC 17 Feb, 1987. Shown are isobars in 4 mb intervals and temperature in degrees C.

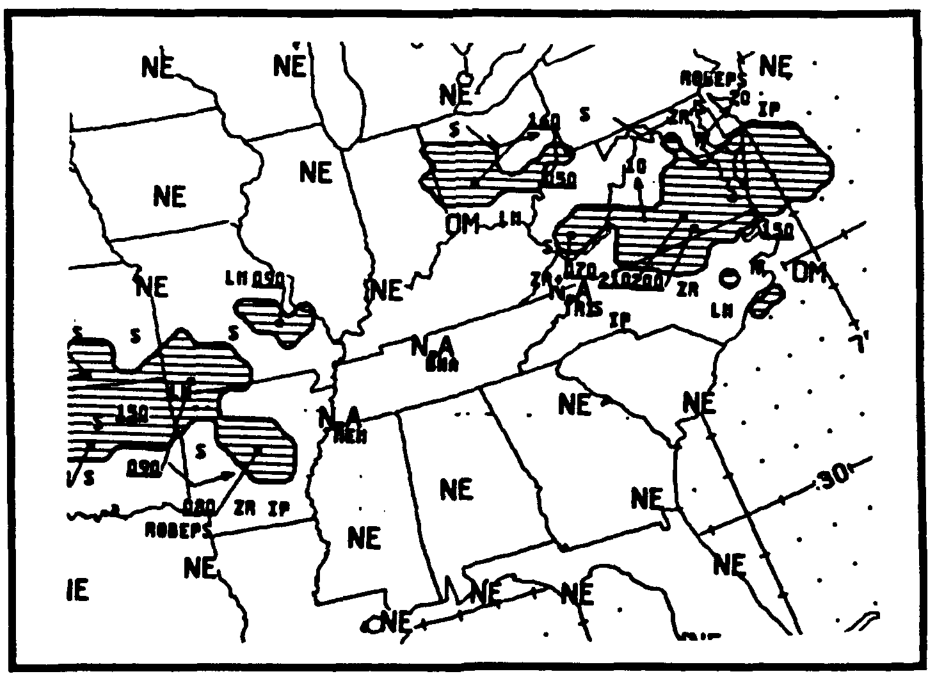

Fig. 12.C: The radar summary for 1235 UTC 17 Feb, 1987

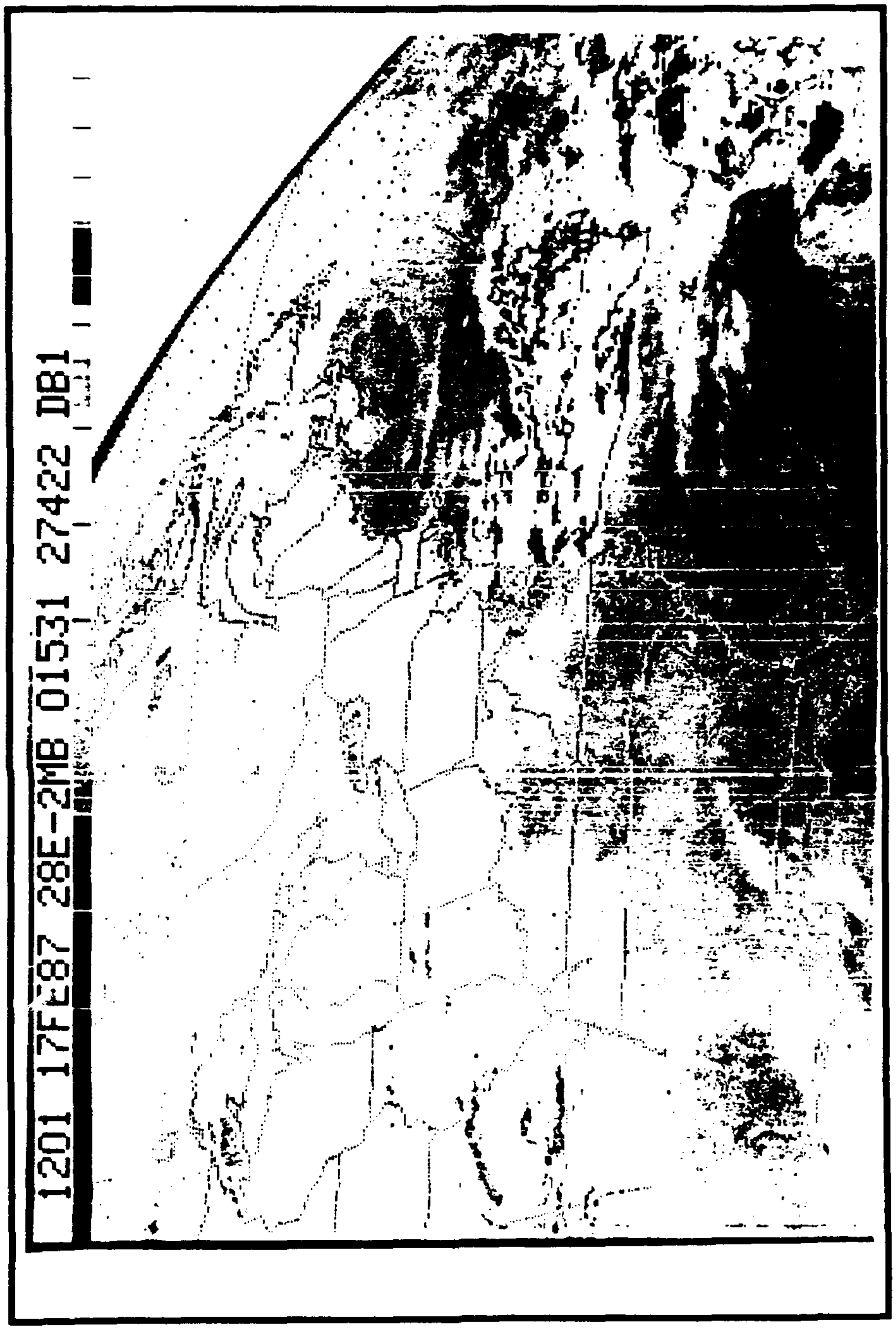

Fig. 12.B: Infrared satellite photo for 1201 UTC 17 Feb. 1987

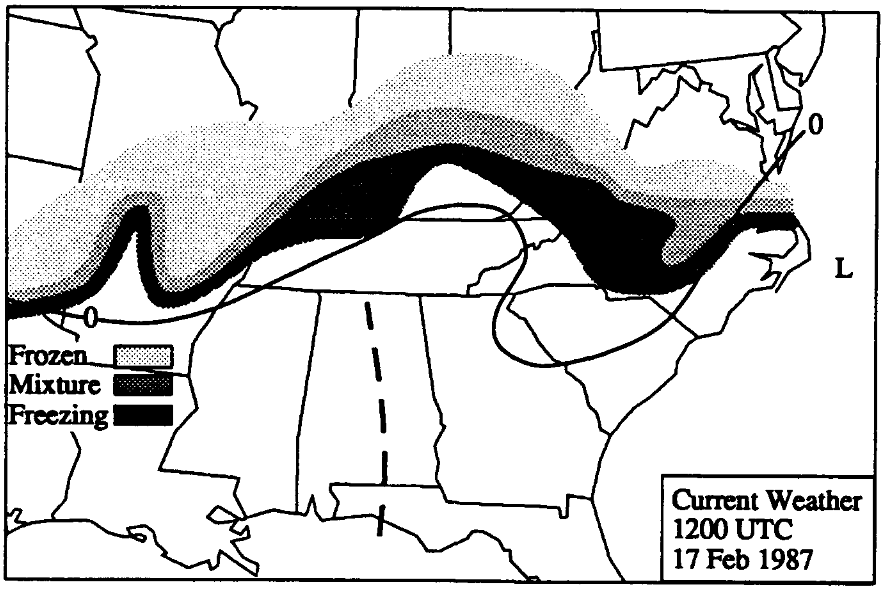

Fig. 12.D: The current weather conditions for 1200 UTC 17 Feb, 1987. Shown is freezing, mixture and frozen precipitation with the 0 degree isotherm.

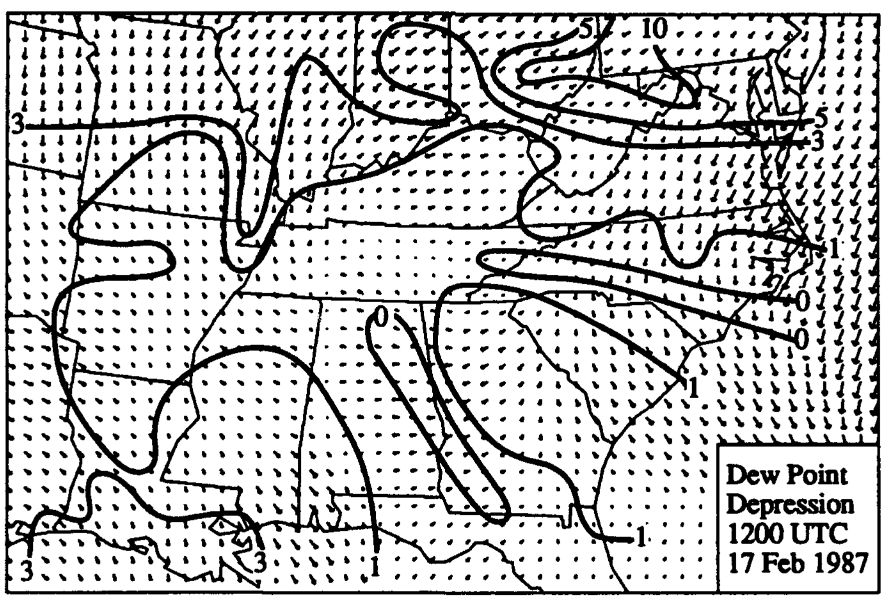

Fig. 12.E: Dew point depression analysis for 1200 UTC 17 Feb, 1987. Shown are dew point depression isopleths in degrees C and wind vectors.

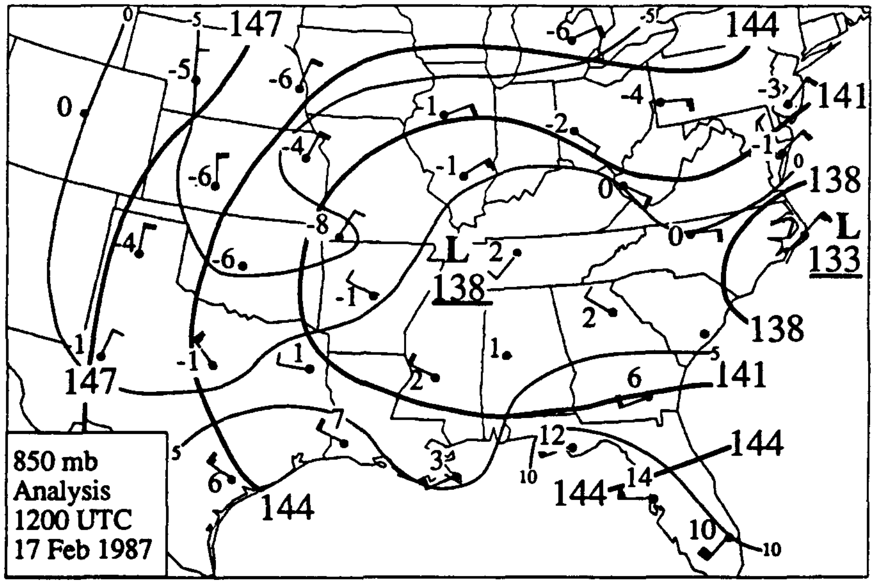

Fig. 13.A: 850 mb analysis for 1200 UTC 17 Feb 1987. Thick lines are 30 m height contours. The thin lines are 5 degrees isotherms.

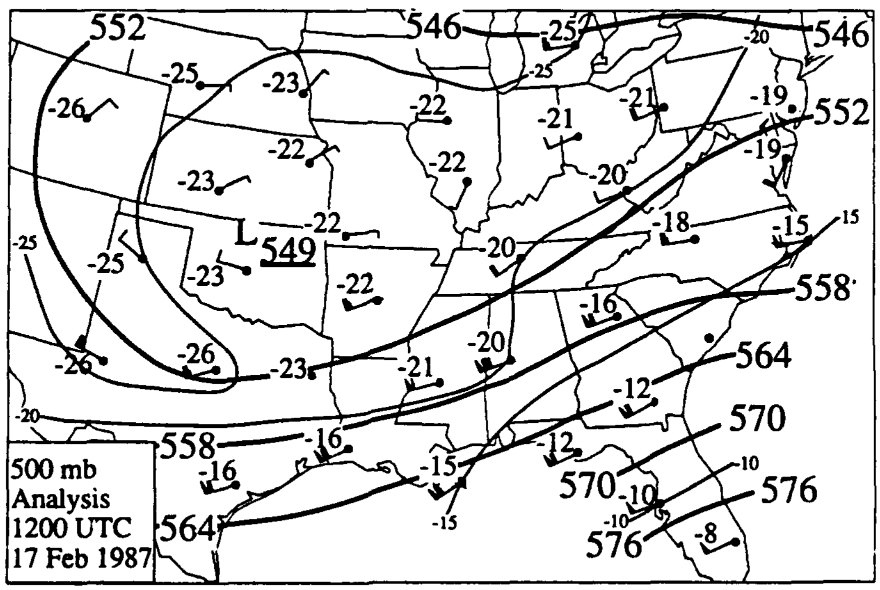

Fig. 13.B 500 mb analysis for 1200 UTC 17 Feb 1987. Thick lines are 60 m height contours. The thin lines are 5 degree isotherms.

completely dissipated. The secondary low was far off the coast of North Carolina with all convective activity over the Atlantic ocean.

1.3 Thickness Analysis

The vertical thickness between isobaric levels is directly proportional to the mean virtual temperature in the layer. It is this temperature structure in the lower troposphere that determines the type of precipitation reaching the ground. The pressure layers typically employed are the 1000-850 mb and 850-700 mb. The former is representative of the air in the shallow cold dome resulting from the cold-air damming. The 850-700 mb layer is representative of the warm air above the cold dome, and in which the precipitation forms. The total 1000-700 mb layer is also used.

A thickness analysis was based on the Greensboro radiosonde station during the sleet event described previously. The 1000-700 mb thickness was 2865 m (0000 UTC, 16 Feb.) and 2864 m (1200 UTC, 16 Feb.). These values are slightly above the range found by Keeter and Cline (1990) for a critical thickness value for an event with a trace of frozen precipitation. At 0000 UTC, 17 February, the 1000-700 mb thickness was 2842 which was within the range for an event with a measurable amount of frozen precipitation. The 850-700 mb thickness values were 1560 m (0000 UTC, 16 Feb.), 1563 m (1200 UTC, 16 Feb.), and 1566 m (0000 UTC, 17 Feb.). All these thickness values were slightly above the critical thickness value range for frozen precipitation events. The 1000-850 mb thickness values for the Greensboro station were 1305 m (0000 UTC, 16 Feb.) and 1301 m (16 Feb.); both of these thickness values are within the critical thickness value range for an event with with a trace of frozen precipitation. The 0000 UTC, 17 February, thickness value was 1276 m which was below the critical thickness range for an event with a mixture of precipitation types with a measurable amount of frozen precipitation.

For a comparison, the Cape Hatteras thickness values were also examined. This station was generally in the warmer air just east of the cold dome. The 1000-700 mb thickness values were 2866 m (0000 UTC, 16 Feb.), 2876 m (1200 UTC, 16 Feb.), and 2909 m (0000 UTC, 17 Feb.). All of these values were above and outside of the range of the critical thickness values for frozen precipitation. The 850-700 mb thickness values were 1557 m (0000 UTC, 16 Feb.), 1566 m (1200 UTC, 16 Feb.), and 1570 m (0000 UTC, 17 Feb.). The 0000 UTC (16 Feb.) thickness was within the critical thickness value range for frozen precipitation; the other two thickness values were above and outside of the critical thickness value range. The 1000-850 mb thickness values were 1309 m (0000 UTC, 16 Feb.) and 1310 m (1200 UTC, 16 Feb.); both of these values were within the critical thickness value range for a trace of frozen precipitation. The 0000 UTC, 17 February, thickness value was 1339 m which was above and outside of the critical thickness value range.

A nomogram was designed by Keeter and Cline (1990) based on 40 years of climatological data for Greensboro. This was specifically designed to differentiate mixed precipitation events producing measurable amounts of frozen precipitation from those producing only a trace of frozen, and also to identify icing events involving freezing rain.

The precipitation type plotted on the nomogram represents the general nature of the precipitation event for the 12-hour period between raob reports. The nomograms indicate the precipitation type as a function of the 1000-850, 850-700, and 1000-700 mb thicknesses. In general, the 1000-700 mb thickness serves to distinguish snow from rain and to differentiate those mixed precipitation events with measurable frozen precipitation from those with only a trace of frozen precipitation. The thicknesses of 1000-850 and 850-700 mb are used to identify icing events involving freezing rain.

Figure 14 shows the precipitation type observed at GSO as a function of the observed thicknesses. The lines separate areas of mostly frozen (Area I) and mostly liquid (Area IV) from mixed precipitation events (Areas II and III). Measurable frozen

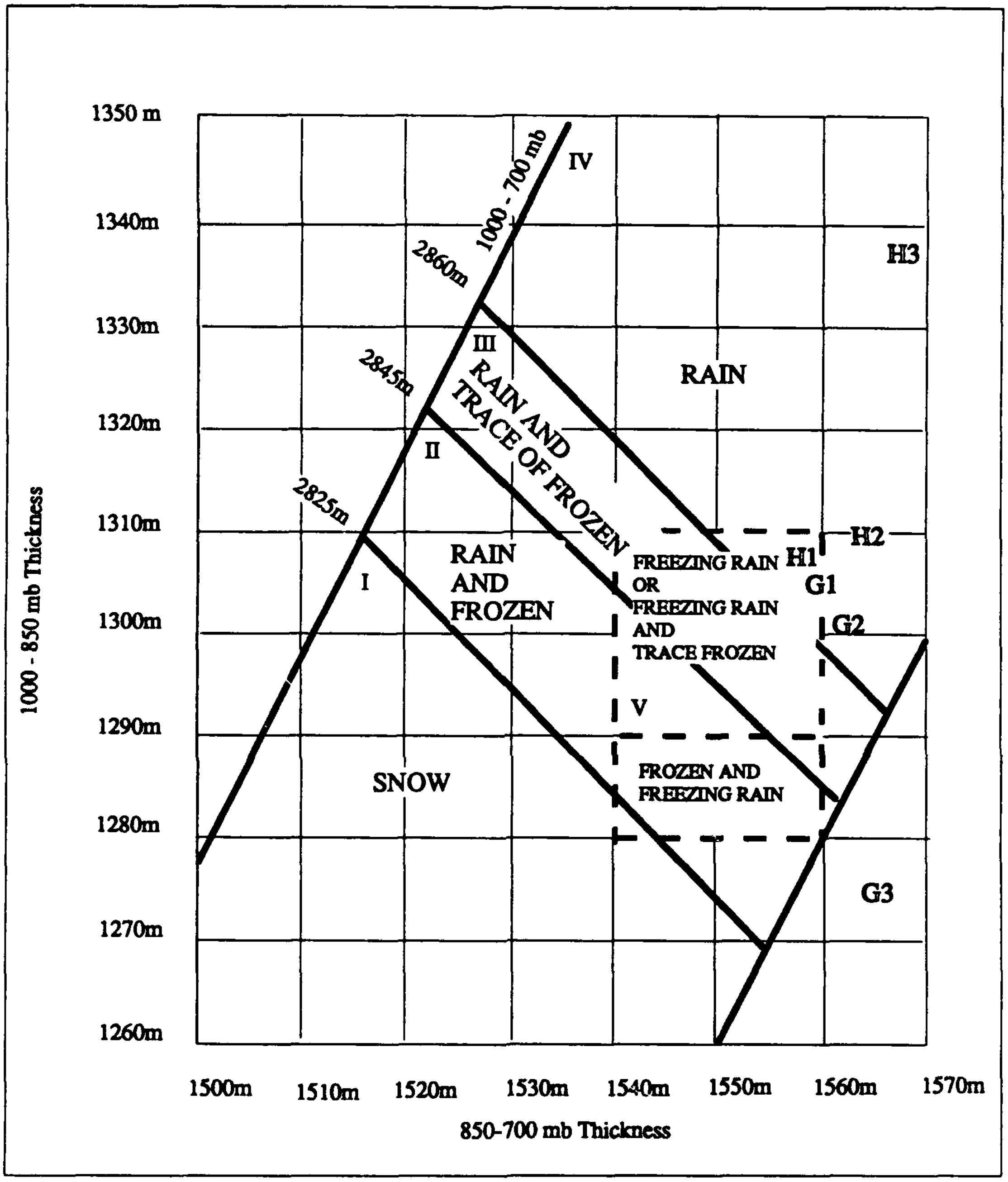

Fig. 14: Nomogram of atmospheric thickness values for Greensboro, NC (G1, G2, G3) and for Cape Hatteras (H1, H2, H3). Thickness is in meters.

precipitation predominates those mixed precipitation events in Area II, while mixed events in Area III generally consist of only a trace amount of frozen precipitation. The dashed area (V) defines an "icy window" that contains the majority of precipitation events involving freezing rain. The lower portion of Area V defines mixed precipitation with freezing rain and frozen precipitation. Sleet is not differentiated from mixed precipitation events.

The letters plotted on the nomogram define where the thickness values occur for the sleet event of 16-17 February, 1987. Letters G1, G2, and G3 define the thickness values for Greensboro with G1 designating the 0000 UTC thickness for 16 February. Letter G2 is the 1200 UTC thickness and G3 is the 0000 UTC thickness for 17 February. Letters H1, H2, and H3 define the thickness values for Cape Hatteras and are plotted as a reference since the nomogram itself was designed for Greensboro thicknesses. Letters H1 and H2 define the 0000 UTC and 1200 UTC thickness values for 16 February. Letter H3 defines the 0000 UTC thickness for the 17th of February.

The uniqueness of the sleet event is evident when viewing the nomogram. The 0000 UTC thickness on 17 February (Letter G3) is much different from the usual precipitation event thicknesses. Since the surface temperature was very cold, the 1000-850 mb thickness was unusually low. Due to the warm air advection aloft, the 850-700 mb thickness was large. Because of this, the combined thickness values did not fall in any of the five areas listed previously. The thickness values for GSO decreased throughout the sleet event, but at HAT, which did not report any precipitation and was outside the cold dome, the thickness values increased.

1.4 Radiosonde Analysis

The 0000 UTC 16 February, 1987 sounding (Fig. 15.A) at Greensboro, North Carolina shows surface temperatures above freezing and surface winds out of the northeast. Above 940 mb, the temperatures are below freezing and then become above 0 ^{o}C to 750 mb. The winds above 850 mb are southwesterly and westerly. The 0000 UTC sounding at Cape Hatteras North Carolina (Fig. 15.B) shows the wind shift at 900 mb but shows much warmer temperatures in the lower levels and greater wind speeds aloft. Both soundings show veering of the winds with height which indicates warm air advection. There is not much difference between the structure of the two soundings as no precipitation is occurring at these stations at this time.

The 1200 UTC 16 February, 1987 sounding at Greensboro (Fig. 16.A) shows an inversion with below freezing temperatures near the surface resulting from diurnal cooling. The temperature structure to about 750 mb is otherwise similar to that of 12 hours earlier. The 1200 UTC sounding at Cape Hatteras (Fig. 16.B) shows primarily above freezing temperatures for the lower levels and a wind shift from northeast to southwest with height. Both soundings continue to show warm air advection based on the veering of the winds with height. Precipitation is entering the state at this time.

The 0000 UTC 17 February, 1987 sounding at Greensboro (Fig. 17.A) shows a strong inversion with very cold temperatures in the lower levels and above freezing temperatures between 730 mb and 860 mb. The remarkable cooling below 860 mb is primarily due to evaporative cooling as precipitation falls into the drier air. The sounding also shows near saturation compared to 12 hours earlier. Surface winds are out of the north and shift to the southwest with height. A jet exists at 850 mb at the base of the inversion. This sounding represents the air under the cold dome. The 0000 UTC sounding at Cape Hatteras (Fig. 17.B) shows above freezing temperatures to 700 mb

and a wind shift from northeast to southwest with height. This sounding represents the air outside the cold dome in the offshore flow. Both soundings show veering of the winds indicating warm air advection.

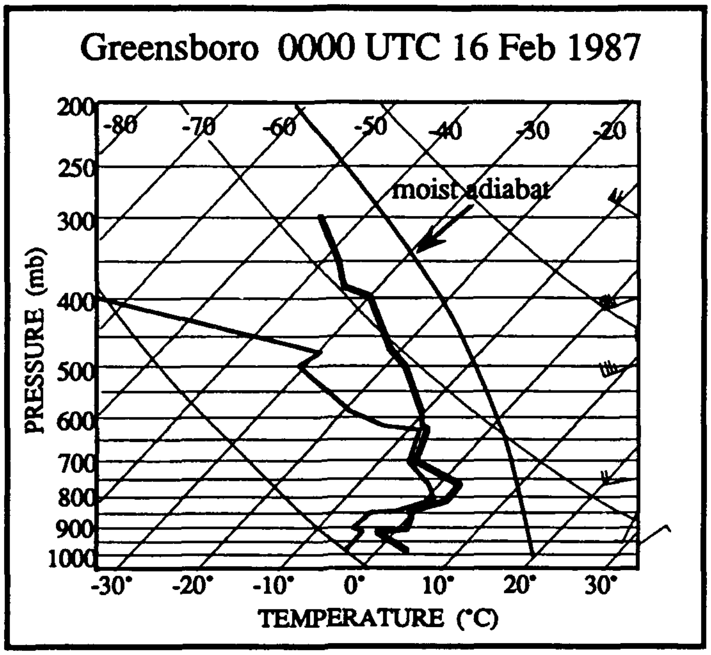

Fig. 15.A: Greensboro, NC sounding for 0000 UTC, 16 February, 1987.

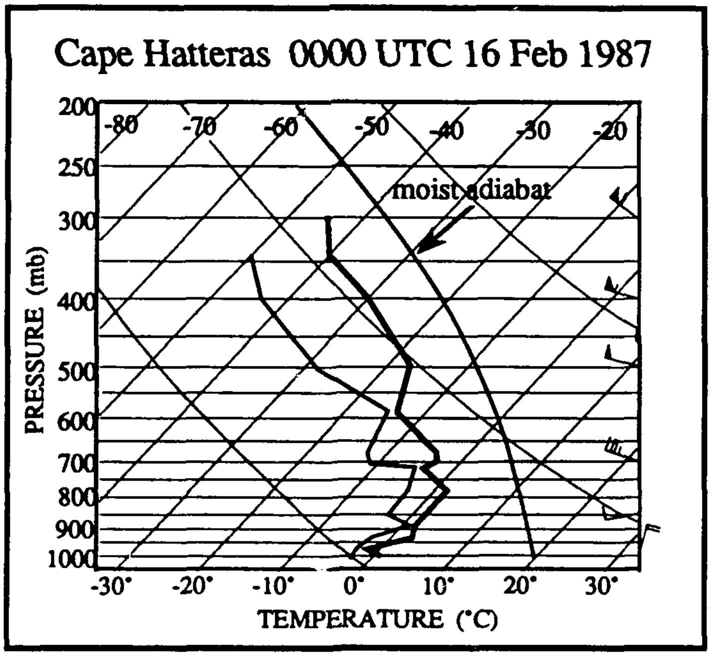

Fig. 15.B: Cape Hatteras sounding for 0000 UTC 16 February, 1987.

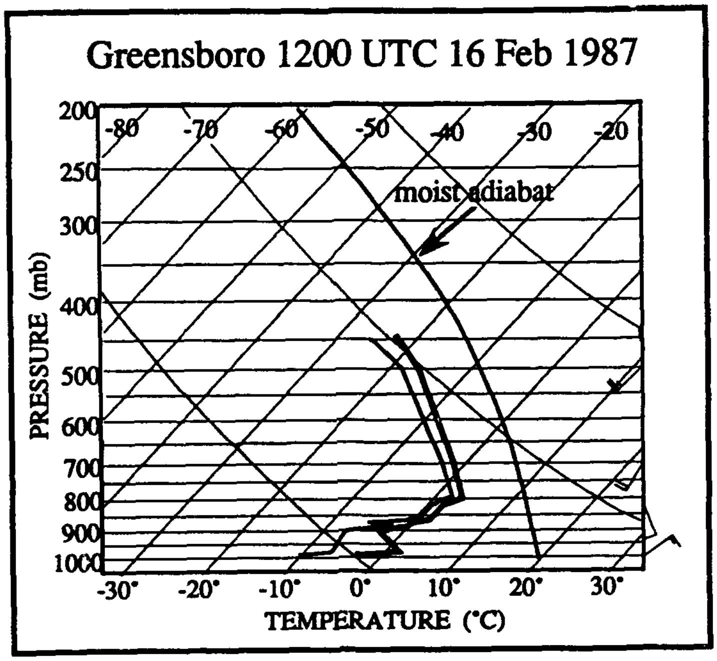

Fig. 16.A: Greensboro sounding for 1200 UTC 16 February, 1987

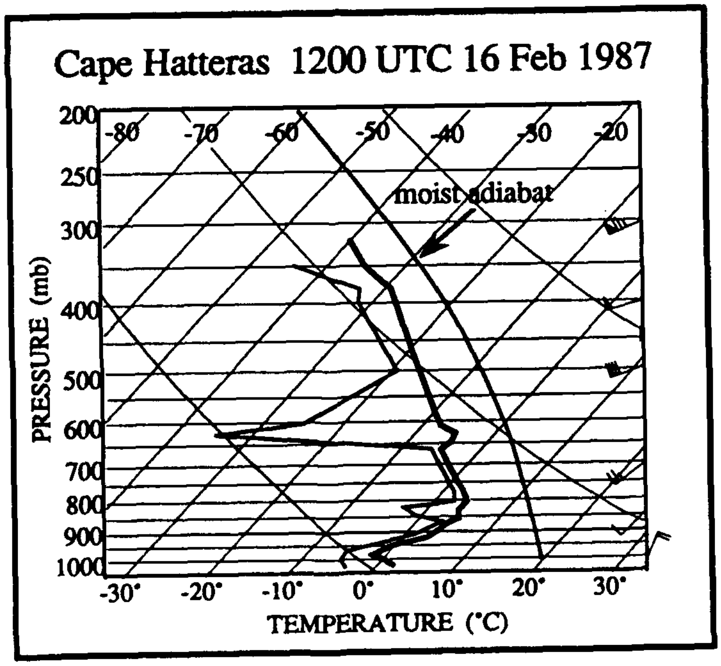

Fig. 16.B: Cape Hatteras sounding for 1200 UTC 16 February, 1987.

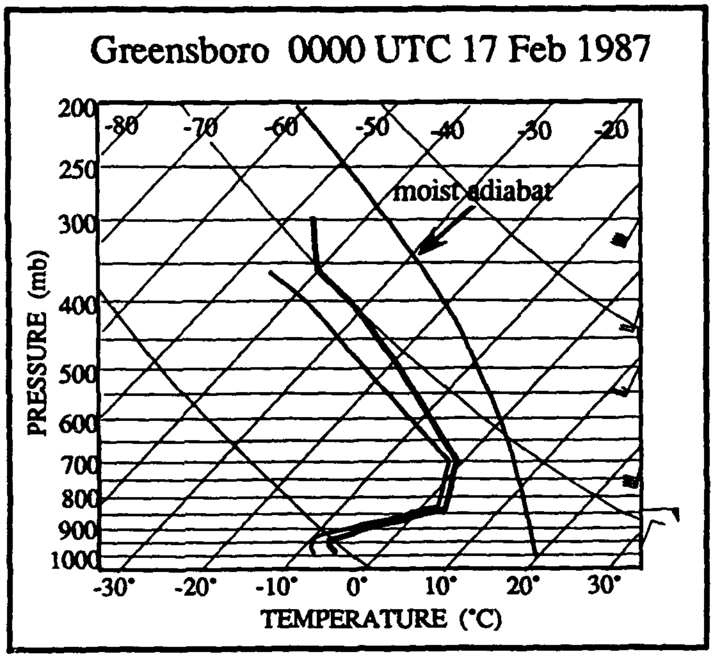

Fig. 17.A: Greensboro sounding for 0000 UTC 17 February, 1987

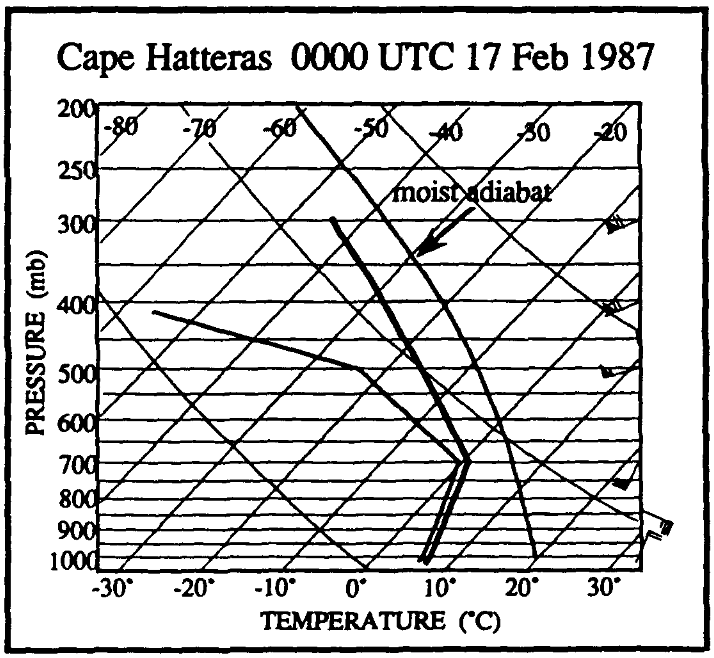

Fig. 17.B: Cape Hatteras sounding for 0000 UTC 17 February, 1987.

2. CLIMATOLOGY OF SLEET EVENTS

2.1 Goals/Objectives

The objectives of the climatology are:

(1) Document sleet events and sleet occurrences for North Carolina for the forty-one winters from 1949/50 to 1989/90 based on the Local Climatological Data (LCD) three hourly data monthly summaries from NOAA.

(2) Investigate trends of sleet occurrences for defined geographic regions of North Carolina. These trends will include documenting the maximum/minimum values, identify daily, monthly and inter-seasonal trends.

(3) Investigate the sequence of precipitation type throughout the events.

(4) Characterize the duration of sleet events and occurrences.

2.2 Methodology and Discussion

Climatological data was obtained for the winters of 1949/50 through 1989/90 for the state of North Carolina from the site specific Local Climatological Data (LCD) monthly summaries published by the National Oceanic and Atmospheric Administration (NOAA). The first order National Weather Service (NWS) stations were used along with several other FAA and military stations across the state to gather data across the state. Secondary stations were substituted for some of the primary stations (Table 1) when data were unavailable in order to keep a complete 24 hour data base for each area. All data were collected from three hourly observations consisting of hours 1, 4, 7, 10, 13, 16, 19, and 22 hours local time and only measurable amounts of frozen precipitation were used, no trace quantities were used. The data are divided into winter seasons (November through April) at each location; i.e. the data for the year 1989 start in November and end in April of 1990.

Until 1985, Rocky Mount was operational from 6 am to 10 pm (EST). Similarly, the station at Elizabeth City was operational from 7 am to 10 pm (EST) until 1983, after which the hours of operation were 8 am to 4 pm (EST). For all other stations, data were collected from a 24 hour data base. See Fig 18 for a diagram showing the station locations.

For the purpose this research a "sleet event" is defined as a winter storm that produced sleet for one or several locations across North Carolina. The duration of the sleet event is defined by the duration of frozen precipitation associated with the particular storm. When ice pellets are observed and recorded in the station's observations, it will be referred to as a "sleet occurrence". See Table 3 for a list of all sleet occurrences for North Carolina from 1949/50 -1989/90.

Location	Identifier	Secondary Station
Asheville	AVL	none
Cape Hatteras	HAT	City of Hatteras
Charlotte	CLT	none
Elizabeth City	ECG	none
Fayetteville	FAY	Pope AFB, Laurinburg
Greensboro	GSO	none
Hickory	HKY	Lenoir
Raleigh-Durham	RDU	none
Rocky Mount	RMT	Wilson
Wilmington	ILM	none

Table 1: The primary and secondary locations used for the climatological survey of sleet events for North Carolina.

LOCATION	NOV	DEC	JAN	FEB	MAR	APR	MAY	TOTAL
AVL	11	33	41	40	23	2	1	151
HKY	8	27	38	29	11	3	0	116
CLT	7	33	46	33	16	1	0	136
GSO	14	46	60	50	28	1	0	199
RDU	11	37	57	36	23	0	0	164
FAY	0	5	16	12	7	0	0	40
RMT	1	14	24	14	10	0	0	63
ILM	2	12	15	16	8	0	0	53
ECG	1	6	11	5	7	0	0	30
HAT	1	5	9	4	3	1	0	23
TOTAL	56	218	317	239	136	8	1	

Table 3: Sleet occurrences for the winters of North Carolina, 1949/50 - 1989/90.

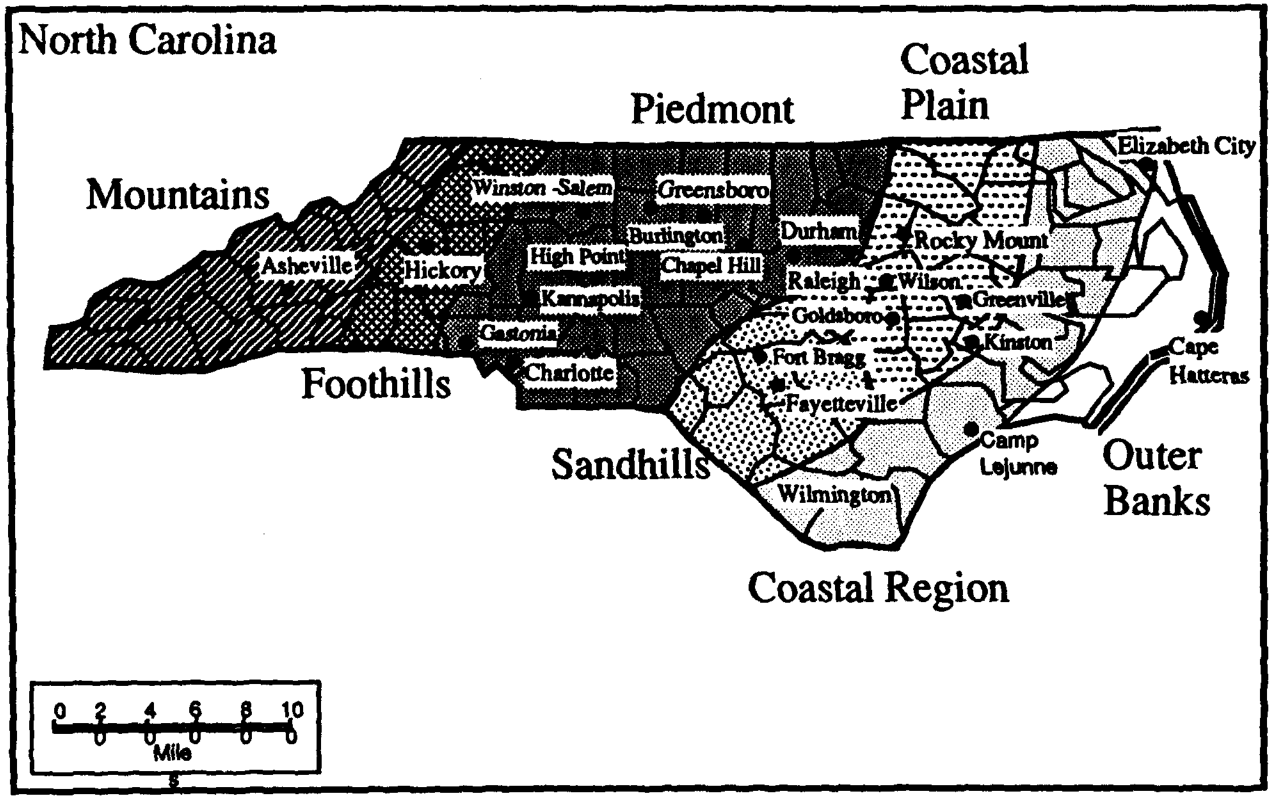

Fig. 18: Geographic regions of North Carolina. Also showing the primary and secondary stations used for the climatology.

For the purposes of constructing the sleet climatology and based on the orographic features of the state, North Carolina was divided into seven geographical regions (Fig. 18). The Mountain region is in the most western part of the state and is represented by the Asheville station. The Foothills are located on the eastern side of the Mountain region and are represented by the Hickory station. The Piedmont region is in the central part of the state and is represented by the stations at Greensboro, Charlotte, and Raleigh-Durham. The Coastal Plain is located on the eastern side of the Piedmont and is represented by the station at Rocky Mount. The Sandhills are located in the southwest corner of the Coastal Plain and is represented by the station at Fayetteville. The Coastal region is on the eastern side of the state and includes the stations at Elizabeth City and Wilmington. The Outer Banks are on the extreme eastern side of the state and borders the Atlantic ocean; this region is represented by the station at Cape Hatteras.

Greensboro recorded the greatest frequency of sleet with 199 occurrences over the 41 year period; Raleigh-Durham is next with 164. It appears from Fig. 19 that sleet occurs most often in the Piedmont region of the state. The Mountain region has the next highest frequency of sleet occurrences with 151 at Asheville. All stations in either the Piedmont, Foothills, or Mountain region had sleet occurrences numbering over 116. There is a dramatic drop in the number of sleet occurrences in the regions east of the Piedmont (Fig. 19). Rocky Mount has the highest recorded number with 63 occurrences followed by Wilmington with 53. Fayetteville, being located in the Sandhills, had a recorded number of 40 occurrences. Elizabeth City, located in the Coastal region, had 30 occurrences. The least recorded number was found at Cape Hatteras, the Outer Banks station, with 23 sleet occurrences. The contours of the sleet occurrences are shown in Fig. 20 along with the elevation contours. The dramatic decrease in sleet occurrences is shown between the Piedmont region and the Sandhills and Coastal Plain region by the strong gradient.

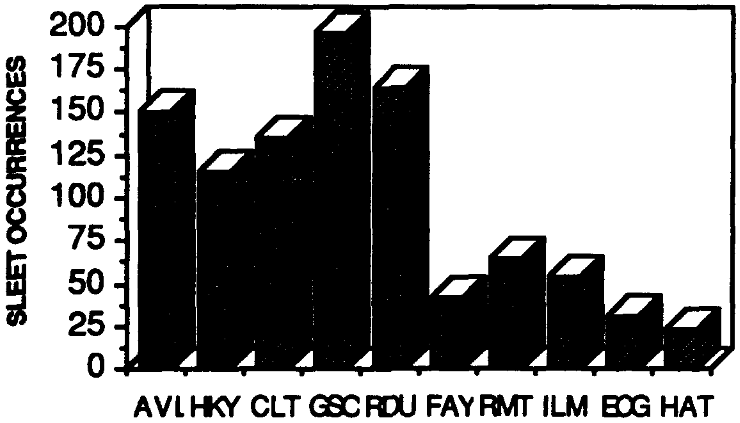

Fig. 19: Sleet occurrences for North Carolina for locations listed in Table 1 for the years of 1949-1989.

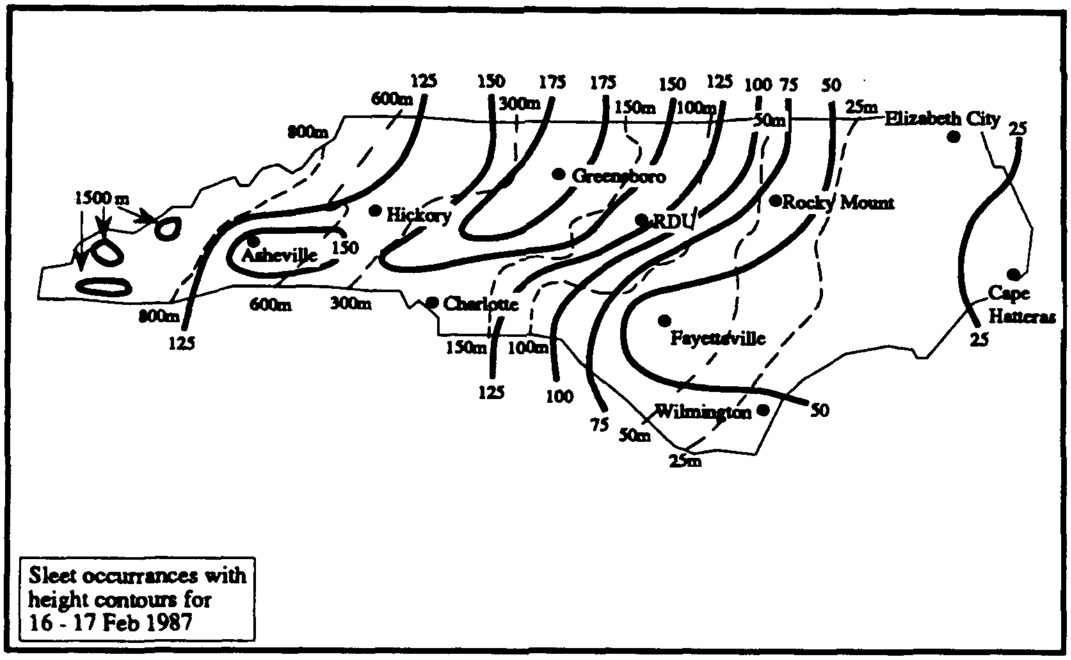

Fig. 20: Contours of North Carolina.Dotted lines are elevation. Solid lines are sleet occurrences.

Sleet events for North Carolina were documented over a six month period from November to April (Fig. 21). There was one exception with Asheville reporting sleet on May 30, 1978. The sleet occurrences were reported in Fig. 22. The earliest in any season that sleet has been recorded was on November 5 (1950) and the latest was on April 29 (1980). The month of January has the highest number of sleet occurrences with 317 occurrences over the entire state of North Carolina over the 41 year period. This is followed by February with 239 occurrences and December with 218. The number of sleet occurrences decreases to 136 in March, 56 in November, and only 8 occurrences being recorded in the month of April.

When looking at the total number of sleet events over North Carolina for the winter seasons from 1949/50 to 1989/90, a trend seems to appear. The total number of sleet events for the 41 year period was 409 or an average of 10 sleet events for the state of North Carolina each year. There also seems to be a decreasing trend of sleet events over the 41 year period (Fig. 23). This coincides with the findings of several studies (Reitan, 1979; Zishka and Smith, 1980; Whittaker and Horn, 1981) that noted a statistically significant decline in the frequency of North American cyclogenesis in recent years. The highest recorded number of sleet events was 19 for the year 1962; the next was 17 for 1963. This was followed by 16 events in 1950, 1961, and 1977. The lowest recorded number of sleet events was 3 for 1975 and 1985. There is a trend of maximums and minimums that appears approximately every 10 years. The maximum values occurred on the years 1950, 1962, 1971, and 1977. The minimum values occurred on the years 1949, 1958 and 1960, 1964, 1975, and 1985. A five year running average was performed on the sleet events and confirms the ten year cycle. A spectral analysis was performed on the five year running average data and a peak was found at the ten year point indicating a ten year cycle. An interesting note is that sleet event minima correspond to El Nino outbreaks. The sleet events minima that occurred in the winters of 1958/59, 1964/65, 1975/76, and 1985/86 also had El Nino outbreaks that occurred in the

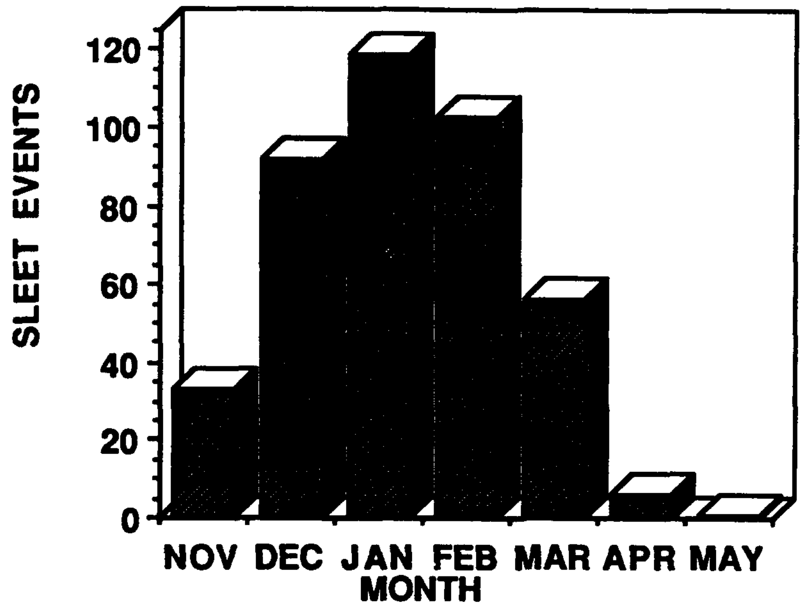

Fig. 21: Monthly sleet events for the winters of North Carolina, 1949-1989.

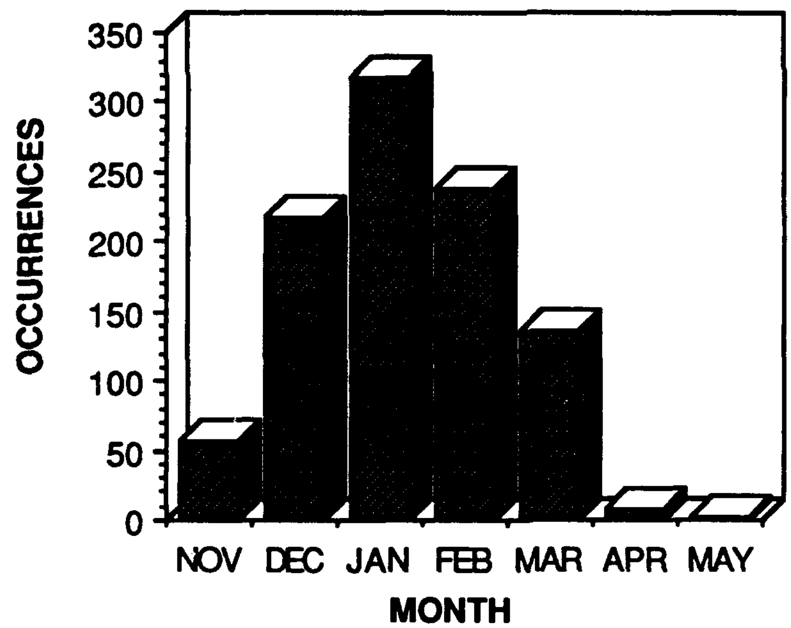

Fig. 22: Monthly sleet occurrences for the winters of North Carolina, 1949-1989.

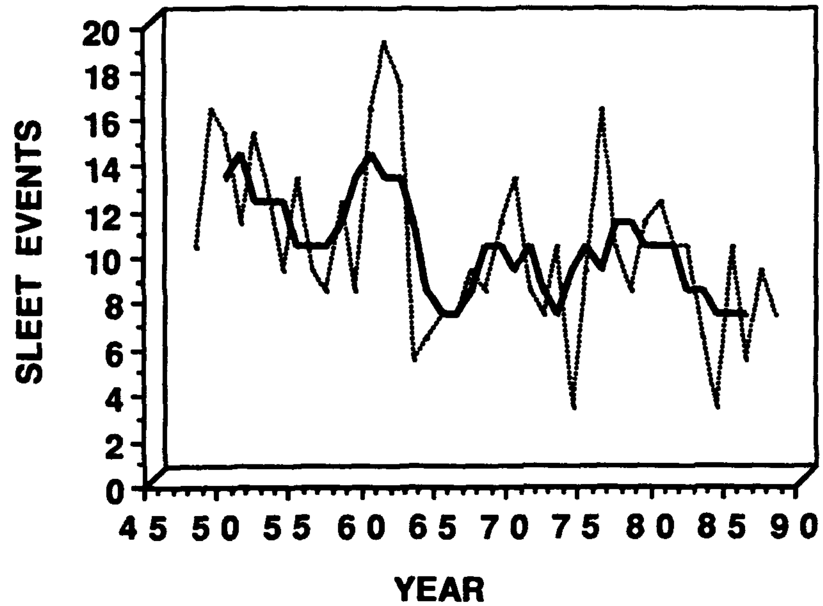

Fig. 23: Yearly sleet events for North Carolina. Solid line is five year running average. Dotted line are actual events.

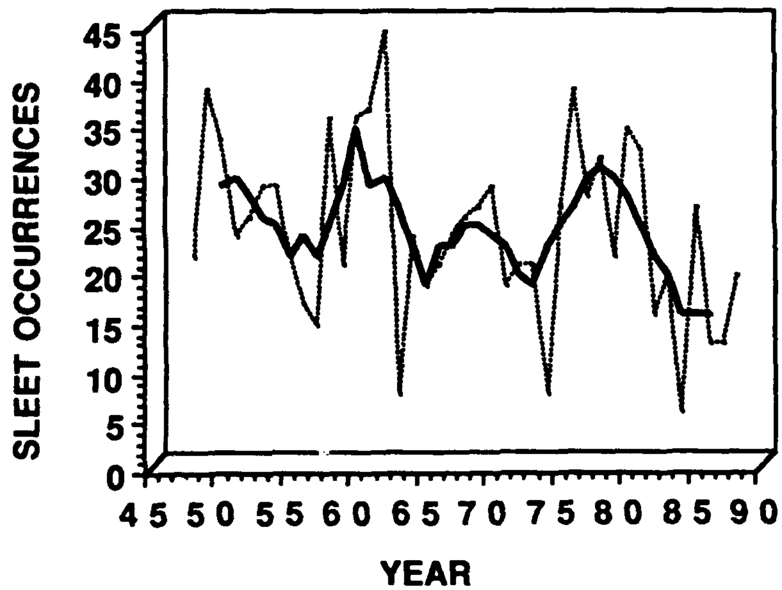

Fig. 24: Yearly sleet occurrences for North Carolina. Solid line is five year running average. Dotted line are actual occurrences.

previous summers. In fact, four of the last six El Nino episodes, dating back to 1948, were also years of sleet event minima. The El Nino outbreaks of 1972 and 1983 were not. A similar look at sunspot activity showed less of a correlation (Hawkins, 1991).

Figure 24 shows the time series of sleet occurrences over North Carolina for the winter seasons of 1949/50 to 1989/90. As with the sleet events, there is a pattern of maxima and minima that occur approximately every ten years. This was also confirmed with a five year running average. A spectral analysis was performed on the five year running average data and a peak appeared at ten years indicating a cycle that appears in the data every ten years. The maximum number of sleet occurrences recorded was forty four in 1963 followed by 38 in 1950 and 1977; The minimum number of recorded sleet occurrences was five in 1985 followed by seven in 1964 and 1975.

One hundred nineteen individual sleet events were examined in detail. In 93 events (78 %), a frontal system, moving west to east, passed across the state. Thirty four events (28 %) had a low pressure system form in the Gulf of Mexico and move up the coast crossing the state. These were classified as Miller type "A" or "B". Twenty nine of these events (24 %) had Miller type "A" lows compared with five of the events (4 %) that had Miller type "B" lows. Forty five of the events (38 %) were influenced by cold-air damming. This was defined by the easterly winds becoming northerly in the southern portion of the high pressure system as the winds encountered the Appalachian mountains. Fifty six events (47 %) had a low pressure system located off the coast of North Carolina as compared to seven events (6 %) which had high pressure off the coast. These were defined by having a closed isobar in the pressure system. Sixty seven events (56 %) had a high pressure system located on the west side of the Appalachian mountains as compared to thirteen events (11 %) that had low pressure.

Sleet occurrences of the individual geographic regions were examined. Figure 25 shows the results for Foothills, Mountains, and Piedmont regions. Figure 26 shows the results for Outer Banks, Sandhills, and Coastal regions. The information was obtained

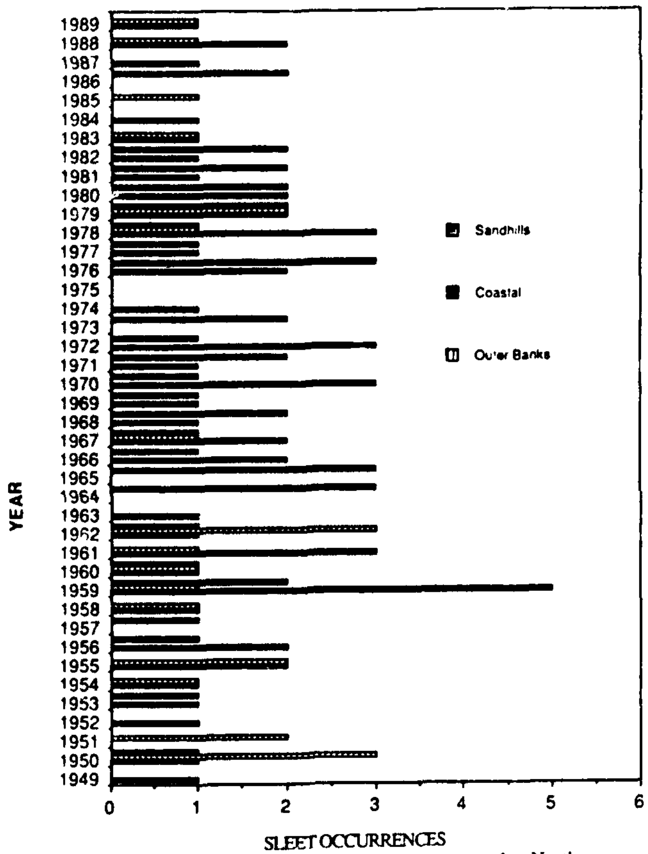

Fig. 26: Regional yearly sleet occurrences for North Carolina; the Coastal, Outer Banks, and Sandhills regions, for the winters of 1949-1989.

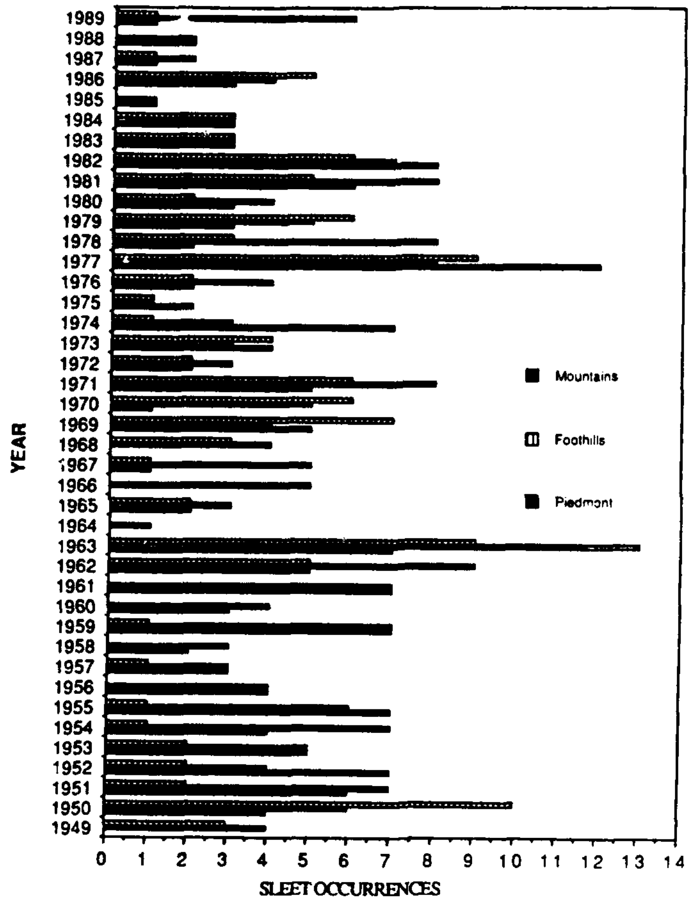

Fig. 25: Regional yearly sleet occurrences for North Carolina; the Foothills, Piedmont, and Mountain regions, for the winters of 1949-1989.

by taking a station within each region which had recorded the highest number of sleet occurrences. Greensboro, Charlotte, and Raleigh-Durham are all within the Piedmont region but Greensboro was used since it had the highest number of sleet occurrences. All stations used were operated on a 24-hr basis; Rocky Mount and Elizabeth City were not used since they are part-time operating stations. The Piedmont, Foothills, and Mountain regions show more sleet occurrences than the Sandhills, Outer Banks, or Coastal regions. It should be noted that 1962 was the only year to have sleet recorded at all locations.

The individual sleet occurrences in the stations observations were also examined. One hundred thirty two sleet observations were examined to show the patterns of precipitation from which the sleet occurrence started and ended. These were from measurable amounts of frozen precipitation from all the stations listed in Table 1; no trace amounts were used. Table 4 shows the results. In 24 % of the observations, the sleet occurrence started in the form of snow, then had an occurrence of sleet, and finally ended in the form of snow. The next highest percentage was 11 % in which the sleet occurrence started in the form of snow and ended in the form of freezing rain. In 10 % the occurrences start as snow and end as rain. In fact, in 54 % the occurrences started in the form of snow; this is followed by 17.4 % which started in the form of sleet (ice pellets). In 16.7 % the occurrence started as rain, in 8 % the occurrence started as freezing rain, and in 4 % the occurrence started as freezing drizzle.

The percentage of sleet observations in the stations observations during sleet events was also examined. The station's observations from the 3-hr LCDs were examined to determine the frequency that sleet appeared in the observation. The hours examined were 1, 4, 7, 10, 13, 16, 19, and 22 (EST). The observations were taken for all stations in Table 1; also only measurable amounts of frozen precipitation were used, no trace amounts were used. In 17 % of the sleet producing storms, the sleet occurred in all (100%) of the observations. In 7 % of the events, sleet appeared in two thirds (67%)

PRECIPITATION TYPE	FREQUENCY	TOTAL
Snow-snow	24 %	Snow = 54 %
Snow-freezing rain	11 %	
Snow-rain	9 %	
Snow-ice pellets	5 %	
Snow-freezing drizzle	3 %	
Snow-drizzle	1 %	
Rain-snow	8 %	Rain = 17 %
Rain-ice pellets	4 %	
Rain-rain	2 %	
Rain-freezing rain	1 %	
Rain-freezing drizzle	1 %	
Rain-drizzle	1 %	
Ice pellets-rain	7 %	Ice pellets = 17 %
Ice pellets-snow	6 %	
Ice pellets-ice pellets	2 %	
Ice pellets-freezing rain	2 %	
Ice pellets-freezing drizzle	1 %	
Freezing rain-snow	2 %	Freezing rain = 8 %
Freezing rain-ice pellets	2 %	
Freezing rain-freezing rain	2 %	
Freezing rain-rain	1 %	
Freezing rain-freezing drizzle	1 %	
Freezing drizzle-snow	2 %	Freezing drizzle = 4 %
Freezing drizzle-freezing rain	2 %	
Freezing drizzle-freez. drizzle	2 %	

Table 4: Patterns of precipitation in sleet occurrences. The left column shows the percentage of sleet occurrences that started and ended with the listed precipitation type coupling. The right column is the starting precipitation type frequency.

of the observations. In 16 % of the events, sleet appeared in half (50%) of the observations.

The frequency distribution of the time of day in which sleet occurred was also examined. Three hundred fifty five hourly observations were examined to determine the hour of day that sleet was more likely to occur. The observations were taken from all stations listed in Table 1. Based upon the data, sleet is most likely to occur in the afternoon. Sleet appeared in hour 16 (EST) in 14.9 % of the events; sleet appeared in hours 13 and 19 (EST) in 14.4 % of the events. Sleet also appeared in hour 10 (EST) in 14.1% of the events. The lowest number of times that sleet appeared in any hour of the day was the first hour (1, EST) in 7.9% of the events. This is shown graphically in Fig. 27.

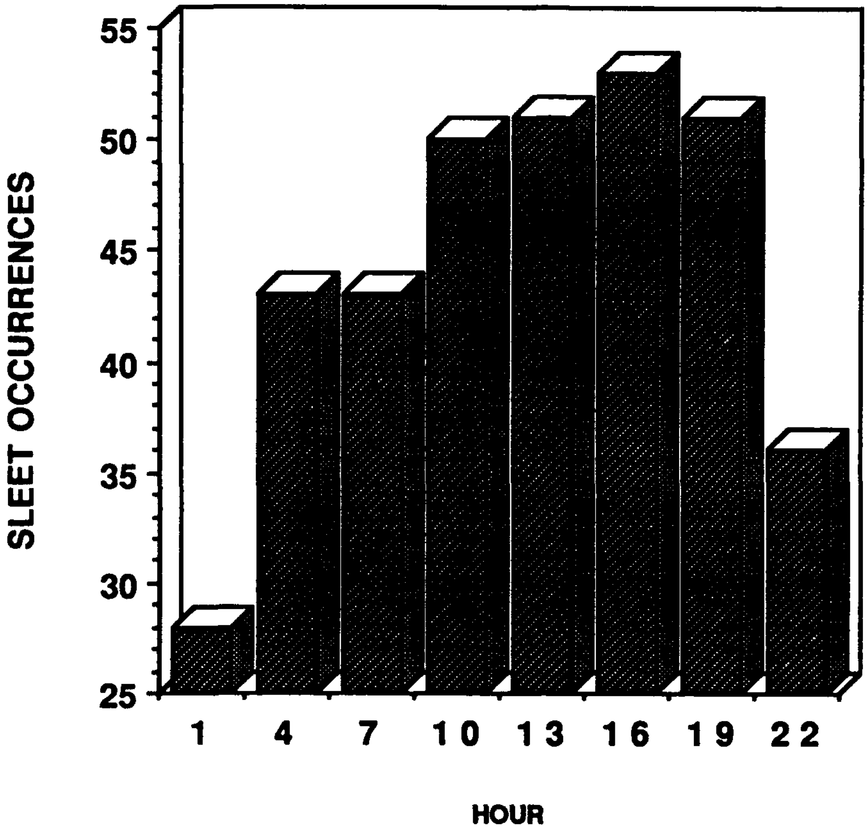

Figure 27: Histogram of hourly sleet occurrences for North Carolina, 1949/50 - 1989/90.

3. DISCUSSION/CONCLUSIONS

The conclusions of the case study are:

(1) Surface high pressure over the Great Lakes resulted in a cold-air damming event along the eastern slopes of the Appalachian Mountains which produced an exceptionally strong northeast jet near the surface.

(2) The northeasterly flow forced a shallow pool of air southward over central Georgia, where a warm front that emminated from a surface low over Mississippi, was encountered. This front was then transformed into a cold front and pushed southward over the Gulf of Mexico.

(3) Aloft a very slow moving closed low centered over the Gulf Coast states resulted in a moderately strong southwesterly jet streak.

(4) Convective activity over the Gulf of Mexico associated with a cold-front aloft (CFA) infused significant moisture into the warm southwesterly jet streak in the mid-troposphere that subsequently overran the cold air.

(5) Upward vertical motion over North Carolina was enhanced by the presence of the left exit region of the jet streak.

(6) The area of mixed precipitation was displaced southward and was broadened as a result of the interaction between the synoptic flow and terrain.

(7) The mixed precipitation band was bounded to north by the 3 DD contour and to the south by the 0 ^{o}C isotherm.

The conclusions of the climatology are:

(1) Sleet is most frequent in the Piedmont region of North Carolina.

(2) North Carolina has a six month sleet season with the greatest frequency of sleet in January.

(3) Fifty five percent of the sleet occurrences over North Carolina start in the form of snow. Seventeen percent start as rain.

(4) Sleet occurs most frequently over North Carolina between 1000 and 1900 EST.

(5) A cycle of maximums and minimums of sleet formation occurs every ten years.

4. FUTURE RESEARCH

1. Continue the climatological study of sleet events. Look at the southeast region to determine if the Piedmont in other states shows a sleet maxima. Go further into history, beyond the 40 year period, to determine if the ten year cycle holds for sleet events. The synoptic patterns should be documented for the sleet events to form a cause and effect research policy.

2. Build upon the descriptive viewing of the sleet event of 16-17 February, 1987 by further researching the dynamics, thermodynamics, and kinematics; this will determine which meteorological features enhanced the movement and formation of the low pressure areas, fronts, and precipitation bands.

5. APPENDIX

5.1 Sleet Occurrences

5.2 Sleet Events

Appendix I

YEAR	EVENTS	OCCURRENCES	AVL	GSO	ILM	HAT
1949	10	21	0	4	1	0
1950	16	38	4	6	1	3
1951	15	33	6	7	0	2
1952	11	23	7	4	1	0
1953	15	25	5	5	1	0
1954	12	28	4	7	1	1
1955	9	28	7	6	2	2
1956	13	21	4	4	2	0
1957	9	16	3	3	0	0
1958	8	14	2	3	1	1
1959	12	35	7	7	5	1
1960	8	20	3	4	1	1
1961	16	35	7	7	3	1
1962	19	36	5	9	1	3
1963	17	44	7	13	1	0
1964	5	7	0	1	0	0
1965	6	23	2	3	0	0
1966	7	18	0	5	2	0
1967	7	20	1	5	2	1
1968	9	23	0	4	1	0
1969	8	25	5	4	1	0
1970	11	26	1	5	3	0
1971	13	28	5	8	1	0
1972	8	18	2	3	3	0
1973	7	20	4	3	0	0
1974	10	20	7	3	1	0
1975	3	7	2	1	0	0
1976	9	26	2	4	2	0
1977	16	38	12	8	1	0
1978	10	27	2	8	3	1
1979	8	31	3	5	2	2
1980	11	21	3	4	2	0
1981	12	34	6	8	1	0
1982	10	32	8	7	1	0
1983	10	15	3	3	1	1
1984	6	19	3	3	1	0
1985	3	5	1	1	0	1
1986	10	26	3	4	0	0
1987	5	12	1	2	1	0
1988	9	12	2	2	2	1
1989	7	19	1	6	1	1

Appendix I

	FAY	HKY	RMT	ECG	CLT	RDU
1949	0	3	3	5	1	4
1950	1	10	4	1	3	5
1951	0	2	3	1	6	6
1952	0	2	2	0	3	4
1953	1	2	2	1	2	6
1954	0	1	4	1	3	6
1955	0	1	2	1	3	4
1956	1	0	3	2	1	4
1957	1	1	0	0	4	4
1958	0	0	2	0	1	4
1959	2	1	4	0	5	5
1960	1	0	4	1	2	3
1961	0	0	5	0	5	7
1962	1	5	4	1	3	4
1963	0	9	2	0	6	7
1964	3	0	2	1	0	0
1965	3	2	2	1	4	6
1966	1	0	2	2	3	3
1967	1	1	1	2	6	0
1968	2	3	1	4	5	3
1969	1	7	1	0	4	2
1970	1	6	1	1	4	4
1971	2	6	0	0	3	5
1972	1	2	1	0	2	4
1973	2	4	1	1	2	3
1974	0	1	0	1	3	4
1975	0	1	0	0	1	2
1976	3	2	1	1	5	6
1977	1	9	0	0	4	3
1978	1	3	1	0	4	4
1979	2	6	2	0	5	4
1980	2	2	1	1	3	3
1981	2	5	0	0	5	7
1982	2	6	0	0	3	5
1983	0	3	0	0	3	1
1984	0	3	0	0	5	4
1985	0	0	0	0	1	1
1986	2	5	2	1	4	5
1987	0	1	0	0	4	3
1988	0	0	0	0	1	4
1989	0	1	0	0	4	5

Appendix 2: The date of the sleet events for the winters of North Carolina, 1949-1989.

YEAR	NOV	DEC	JAN	FEB	MAR	APR	TOTAL
49	22	15	16,27	26	7,16,20,4,13		10
50	11,22,24,28	9,22,28,4,26,30	13,23,31	2,9	12		16
51	26,6	14,18,20,22	8,22	15,24,26	2,18,15,24		15
52	30	2,11,30	11	21,24,2,28	1,3		11
53	5	5,12,14,19,22,25	5,11,16,22,14	3,8,28			15
54	27	5,12	10,15,18,21,24	5,8,11	19		12
55	10,19,25	1	9,19,23	1,6			9
56	26	29	15,20,17,24	11,15	1,4,21,6	8	13
57		11	7,29,24	5,7,15	13,18		9
58		11,14	8,16	3	16,29,2		8
59	30	23	4,26	4,13,21,25	2,9,15,11		12
60		10	3,19,26,29	3,7	18		8
61	18	7,9,14,28	1,12,18,10,28	11,13,21	2,5,9		16
62	5	21,24,29	5,13,19,23,29	1,3,8,17,12,19,24,26	11,15		19
63	29	2,11,14,29,22,31	1,11,13,17	10,15,25,28	21	2	17
64		20	15,31	14,30			5
65			15,22,26,29	23,24			6
66		12,24,28,30		6,9,28			7
67			1,6,9,11,13,24	23			7
68	10	8		15,22,28,17	1,6,9		9
69		6,21,25	6,11,19,1	14			8
70	23	16,31,29	24,8	3,4,7,13	25		11
71	9,23,27	3,24,28	1	1,3,17,8,18,23			13
72	16	25,16	7,10	27,9	21		8
73		8,15	14	3,16	12,25		7
74	30	15,19	6,20	3,4	1,9,11		10
75	23	25	27				3
76	14	6,8	3,5,7,9,24	18			9
77	27	30,21	8,12,17,19,20	2,13,16,19,28	2,12		15
78	26	24	12,19,27,31	6,18,20,26			10
79			1,4,30,13	9	1,12	29	8
80	27	27	6,30,21	1,4,11,20	4,22		11
81		4,21,25,31	13,14,16,22	12,26	7	8	12
82		12,19,30	9,21	6,10,14	26,24		10
83		20,27,31	11,13,15,23,30	22,27			10
84		8	10,16,27	5	22		6
85		25	29	14			3
86	13,15	12	1,25,21	16,26,17		3	10
87	11		2,3,7,25				5
88		12,16,9,30	9	17	8,22	11	9
89		7,9,12,15,18		26	20		7
TOTAL	33	92	119	103	56	6	409

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